Water Ecosystem Services under the Effect of Water Scarcity in the Drâa Basin in Morocco: Assessment of Local perceptions and Economic Valuation towards an Integration into Regional Decision-making processes

by
Imane Mahjoubi
from Arfoud / Morocco

Accepted Dissertation thesis for the partial fulfillment of the requirements for a
Doctor of Natural Sciences
Fachberich 7: Natur- und Umweltwissenschaften
PRTU Kaiserslautern-Landau

Examination date: 30/09/2024

Department: Natur- und Umweltwissenschaften

Examination Board: Prof. Dr. Oliver Frör
Dr. Lisa Bossenbroek

Chairperson of the examination board: Prof. Dr. Andreas Lorke

Dean of the Faculty: Prof. Dr. Oliver Frör

Declaration

I declare that I have written the dissertation entitled "Water Ecosystem Services under the Effect of Water Scarcity in the Drâa Basin in Morocco: Assessment of Local Perceptions and Economic Valuation Towards an Integration into Regional Decision-making Processes" independently, and all aids and sources used for the thesis have been indicated. Contributions from any collaborators and other authors are clearly labeled.

I declare that I have not used the paid assistance of mediation or counseling services (including doctoral advisors or other persons).

I declare that I have not submitted the dissertation in the same or a similar form as an examination paper for a state or other academic examination in Germany or abroad. I have not submitted the same or a different dissertation to another faculty or academic institution as a dissertation.

I am aware that a violation of any of the aforementioned points may result in the withdrawal of the doctoral degree and may also have further legal consequences.

I declare the use of DeepL Translate [DeepL.com] to generate translations of key terms in the preparation of this assessment. I acknowledge the use of ChatGPT [https://chat.openai.com/], DeepL Write, and Grammarly in helping me review my writing at the final stage of preparing my assessment. I used the following features: clarity, correctness, and readability. I reviewed the feedback generated critically and, based on this, revised the writing using my own words and expressions.

Imane Mahjoubi

Landau, 04/11/2024

Table of Contents

List of Publications

This thesis consists of four articles, which are introduced below. The formatting required by the journal was removed, spelling mistakes were corrected and all sections, figures, and tables were re-numbered to fit into a common layout for inclusion in this manuscript. The references of each chapter have been combined into a single list of references at the end of this thesis. The research was funded by the "SALIDRAA 2" project under the Social-Ecological Research Programme of the German Federal Ministry of Education and Research (grant no. 01UU1906).

Article 1 – Chapter 2 (Published)

Mahjoubi, I.; Bossenbroek, L.; Berger, E.; Frör, O. Analyzing Stakeholder Perceptions of Water Ecosystem Services to Enhance Resilience in the Middle Drâa Valley, Southern Morocco. Sustainability 2022, 14, 4765.

Article 2 – Chapter 3 (Revisions submitted: May 29th, 2024)

Mahjoubi, I., Frör, O. Ecosystem service change from lost surface water for farming in the Middle Drâa valley, southern Morocco: An economic valuation through a Replacement Cost Approach.

Article 3 – Chapter 4 (Published)

Kaczmarek, N., I. Mahjoubi, M. Benlasri, M. Nothof, R. B. Schäfer, O. Frör, & E. Berger, 2023. Water quality, biological quality, and human well-being: Water salinity and scarcity in the Drâa River basin, Morocco. Ecological Indicators Elsevier 148: 110050.

Article 4 – Chapter 5 (Submitted: March 19th, 2024)

Silva-Novoa Sanchez, L. M.; Mahjoubi, I.; Frör, O.; Bossenbroek, L.; Schilling, J. P.; Berger, E.; Groundwater governance in the Middle Drâa Valley of Morocco: A social-ecological system and incentive analysis.

Acknowledgments

This dissertation is the culmination of a challenging yet rewarding journey, and I owe a debt of gratitude to many who have supported and encouraged me along the way.

First and foremost, I would like to express my deepest gratitude to my family for their unconditional support. To my father, mother, and sisters, your constant encouragement and belief in my abilities have been a source of strength throughout my time in Germany. Your love and support have been invaluable.

I extend my gratitude to my colleagues and supervisors, whose work spirit and commitment to learning have been truly inspiring. Special gratitude goes to my main supervisor, Oliver, whose insightful feedback and valuable supervision have guided me through the complexities of my research and fieldwork. Your expertise and patience have been instrumental in shaping the present research.

To my friends in Landau, thank you for the wonderful and enjoyable times we shared. Your companionship has made life here much easier and filled with joy. The memories we created together are cherished and have provided a much-needed balance to my academic pursuits. From our spontaneous music sessions and outdoor activities to our unforgettable travels, each moment has been a treasure. Whether we were enjoying picnics in the park, or simply relaxing and sharing stories over a meal, these experiences brought laughter and joy into my life. Your support and camaraderie have been a constant source of motivation and happiness.

A very special gratitude goes to my best friend, colleague, love, and partner in life, Luis. Your unwavering support, love, and the countless great memories we have made together have been a meaningful foundation for my journey in Landau. The delicious food you prepared not only nourished my body but also lifted my spirits, helping me persevere through the challenges of this PhD. I am deeply grateful for your presence in my life and for everything you have done to make this accomplishment possible.

Each of these individuals and experiences has left an indelible mark on my journey, and I am deeply thankful for their contributions to my personal and academic growth.

Summary

The relationship between human well-being and water is crucial. Water provides essential resources, regulates the environment, and maintains cultural significance. In Morocco's Middle Drâa Valley (MDV), drought, extreme climate, and intensive agriculture are exacerbating water degradation and creating environmental and social challenges. Human interventions often prioritize immediate needs including drinking and irrigation over other services. Freshwater allocation, especially groundwater, is further complicated by recent over-exploitation and depletion of water tables. In the MDV of southeastern Morocco, the challenge of balancing the allocation of freshwater to oases and the maintenance of essential services is evident. This dissertation aims to contribute to this debate through the practical application of the ecosystem services (ESS) concept within a social-ecological systems (SES) framework, with a focus on human-water interactions. It aims to identify the ESS of water provided to the MDV oases, assess and contrast the perceptions of stakeholders on these services, and provide recommendations for water allocation strategies. Focusing on MDV's identity as an irrigated agriculture region, the research also estimates the value of surface irrigation water, reflecting losses suffered by shifting from surface to groundwater use. The Replacement Cost Approach (RCA) is tested for this purpose. In addition, this thesis examines possible relationships between measured water quality, ecological health, and community satisfaction in different areas of the Drâa basin. Furthermore, and always with a focus on water resources, the opportunities and challenges of groundwater governance in different SES will be explored. The aim is to understand user behavior and compliance with water use regulations, with emphasis on the role of incentive-based mechanisms for sustainable water use. The present research is based on qualitative and quantitative field research, using semi-structured and standardized interviews, focus group discussions, and observations, which are then transcribed and analyzed using content analysis and statistics.

Chapter 2 reveals shared priorities and differences in water-related ecosystem services (ESS) perceptions between governmental actors and local inhabitants in the Moroccan Middle Drâa Valley (MDV). Both prioritize drinking water and irrigation, but governmental officials often overlook regulating and cultural services. This suggests the need for better stakeholder dialogue and consideration of power dynamics and governance structures. Locals primarily focus on securing adequate water for agriculture, often resorting to alternative sources when surface water is insufficient. Based on this, testing the RCA, in Chapter 3, reveals the varying costs farmers face, with larger farms benefiting from economies of scale, thus highlighting the need for targeted government programs to support small-scale farmers. Here, the RCA is a valuable tool for understanding farmers' behavior and decision-making in response to water scarcity and droughts, while acknowledging the limitation stemming from the absence of data on non-recovered and several factors that determine and motivate well-drilling that may not be directly related to surface water loss. This points out the necessity for future research to refine these estimations and fully understand the impacts of water scarcity in the MDV considering all possible variables. Analyzing the impact of water quality on ecosystems and human well-being shows both direct and indirect effects, such as the emotional distress caused by saline river water as exhibited in Chapter 4. It concludes that establishing a definitive link between ecosystem status and human well-being remains complex, indicating the need for comprehensive surveys to capture these interactions more accurately. At this point of the research, it becomes evident that groundwater is the main source of irrigation in the MDV's social-ecological systems, and that its current usage and exploitation urgently require immediate action. Following this, the groundwater governance systems analysis conducted in Chapter 5 reveals the benefits

and drawbacks of current hierarchical and self-governance models identified through three case studies in the MDV. The incentive adequacy analysis of governance rules and laws shows that the hierarchical model struggles with rule compliance due to discrepancies between state regulations and local realities and weak sanctioning mechanisms, which reduces drastically the efficacy of incentives. In contrast, self-governance, observed in M'hamid and Faija, demonstrates higher compliance rates due to well-defined user communities that mutually agree on regulating resource use. The aquifer contract in Faija, located in the extensions of the oases and which combines both models, highlights participation inadequacies, stressing the importance of local stakeholder engagement and natural incentives for effective implementation. This combined approach suggests that adaptive governance, aligned with local contexts, can foster a more inclusive and effective groundwater management system, ultimately supporting the sustainability of the MDV.

In summary, this dissertation underscores the potential of recognizing diverse perceptions and points of view to foster stakeholder communication in the MDV. It advocates for acknowledging power dynamics in learning and knowledge exchange. The ESS approach offers a comprehensive understanding of the interplay between human activities and water dynamics in the MDV. It helps demonstrate the challenges and consequences endured by small-scale farms in arid regions and advocates for targeted incentives to improve water resource management for this critical and overlooked category. While institutional diversity in groundwater governance proves valuable, this research suggests that a cohesive system may ultimately be necessary to coordinate efforts effectively. The aquifer contract in Faija is identified as a promising model but requires further adjustments to optimize its effectiveness. Past experiences of the Moroccan government in aquifer contracts clearly emphasize this necessity. Here comes the role of incentives in driving behavioral changes and compliance in water-stressed areas, taking into consideration a social-ecological perception for a holistic analysis. Ultimately, this research challenges conventional water management practices and promotes more nuanced, inclusive, and effective governance strategies. By contributing to the global discussion on water ESS assessment, it aims to ensure a sustainable and continuous supply of essential ecosystem services, enhancing human well-being in water-scarce regions.

Zusammenfassung

Die Beziehung zwischen menschlichem Wohlbefinden und Wasser ist entscheidend, da Wasser notwendige Ressourcen bereitstellen, die Umwelt reguliert und kulturelle Bedeutung bewahrt. Im marokkanischen Mittleren Drâa-Tal (MDV) verschärfen aride Bedingungen die Verschlechterung der Wasserökosysteme durch Klimaextreme und intensive Landwirtschaft, was ökologische und soziale Herausforderungen mit sich bringt. Menschliche Eingriffe priorisieren oft unmittelbare Bedürfnisse wie Trinkwasser und Bewässerung gegenüber anderen Diensten. Die Verteilung von Süßwasser, insbesondere Grundwasser, wird durch Übernutzung und Erschöpfung des Grundwasserspiegels komplexer. Im MDV in Südostmarokko ist die Herausforderung, die Zuteilung von Süßwasser für Oasen und die Aufrechterhaltung wesentlicher Dienstleistungen in Einklang zu bringen, deutlich sichtbar. Diese Dissertation trägt zu dieser Debatte bei, indem sie das Konzept der Ökosystemleistungen (ESS) im Rahmen eines sozial-ökologischen Systems (SES) praktisch anwendet und sich auf Mensch-Wasser-Interaktionen konzentriert. Ziel ist es, die Wasser-ESS, die den Oasen im MDV zur Verfügung stehen, zu identifizieren, die Wahrnehmungen der Interessengruppen zu bewerten und Empfehlungen für Wasserzuteilungsstrategien zu geben. Darüber hinaus schätzt die Forschung den Wert der Oberflächenbewässerung für Landwirte und reflektiert die Verluste durch den Wechsel von Oberflächen- zu Grundwassernutzung mittels des Ersatzkostenansatzes (RCA). Die vorliegende Dissertation untersucht auch potenzielle Zusammenhänge zwischen gemessener Wasserqualität, ökologischer Gesundheit und der Zufriedenheit der lokalen Gemeinschaften in verschiedenen Gebieten des Drâa-Flussbeckens. Darüber hinaus werden die Möglichkeiten und Herausforderungen der Grundwasserbewirtschaftung in verschiedenen SES untersucht, um das Nutzerverhalten und die Einhaltung von Wassernutzungsregeln hervorzuheben, wobei der Schwerpunkt auf Anreizmechanismen für eine nachhaltige Nutzung liegt. Die Forschung basiert auf qualitativer und quantitativer Feldforschung mit halbstrukturierten und standardisierten Interviews, Fokusgruppendiskussionen und Beobachtungen, die anschließend transkribiert und mittels Inhaltsanalyse und Statistik ausgewertet werden.

Kapitel 2 zeigt gemeinsame Prioritäten und Unterschiede in den Wahrnehmungen der Ökosystemdienstleistungen (ESS) im Zusammenhang mit Wasser zwischen staatlichen Akteuren und lokalen Bewohnern im marokkanischen Mittleren Drâa-Tal (MDV). Beide Gruppen priorisieren Trinkwasser und Bewässerung, aber staatliche Beamte übersehen oft regulierende und kulturelle Dienstleistungen. Dies deutet auf die Notwendigkeit eines besseren Dialogs zwischen den Interessengruppen und die Berücksichtigung von Machtverhältnissen und Governance-Strukturen hin. Die Einheimischen konzentrieren sich hauptsächlich darauf, genügend Wasser für die Landwirtschaft zu sichern und greifen oft auf alternative Quellen zurück, wenn Oberflächenwasser unzureichend sind. Basierend darauf zeigen die Tests der Ersatzkostenmethode (RCA) in Kapitel 3 die unterschiedlichen Kosten, denen die Landwirte gegenüberstehen, wobei größere Betriebe von Skaleneffekten profitieren. Dies unterstreicht die Notwendigkeit gezielter Regierungsprogramme zur Unterstützung kleinerer Landwirte. Die RCA ist ein wertvolles Instrument zum Verständnis des Verhaltens der Landwirte und ihrer Entscheidungsfindung als Reaktion auf Wasserknappheit und Dürren, wobei anerkannt wird, dass Daten zu nicht wiedergewonnenen Verlusten und zu verschiedenen Faktoren, die das Bohren von Brunnen bestimmen und motivieren, fehlen, die möglicherweise nicht direkt mit dem Verlust von Oberflächenwasser zusammenhängen. Dies verdeutlicht die Notwendigkeit zukünftiger Forschung, um diese Schätzungen zu verfeinern und die Auswirkungen der Wasserknappheit im MDV unter Berücksichtigung aller möglichen

Variablen vollständig zu verstehen. Die Analyse der Auswirkungen der Wasserqualität auf Ökosysteme und das menschliche Wohlbefinden zeigt sowohl direkte als auch indirekte Effekte, wie die emotionale Belastung durch salzhaltiges Flusswasser, wie in Kapitel 4 dargestellt. Es wird festgestellt, dass die Herstellung einer eindeutigen Verbindung zwischen dem Zustand des Ökosystems und dem menschlichen Wohlbefinden komplex bleibt, was die Notwendigkeit umfassender Umfragen zur genaueren Erfassung dieser Wechselwirkungen aufzeigt. Zu diesem Zeitpunkt der Forschung wird deutlich, dass Grundwasser die Hauptquelle für Bewässerung in den sozio-ökologischen Systemen des MDV ist und dass die aktuelle Nutzung und Ausbeutung dringend Handlungsbedarf erfordert. Die Analyse der Grundwassermanagementsysteme in Kapitel 5 zeigt die Vor- und Nachteile der aktuellen hierarchischen und Selbstverwaltungsmodelle, die durch drei Fallstudien im MDV identifiziert wurden. Die Analyse der Anreizangemessenheit von Governance-Regeln und -Gesetzen zeigt, dass das hierarchische Modell mit der Einhaltung der Regeln aufgrund von Diskrepanzen zwischen staatlichen Vorschriften und lokalen Realitäten sowie schwachen Sanktionsmechanismen zu kämpfen hat, was die Wirksamkeit der Anreize drastisch reduziert. Im Gegensatz dazu zeigt die Selbstverwaltung, wie sie in M'hamid und Faija beobachtet wird, höhere Compliance-Raten aufgrund gut definierter Benutzergruppen, die sich gegenseitig auf die Regulierung der Ressourcennutzung einigen. Der Aquiferkontrakt in Faija, der in den Erweiterungen der Oasen liegt und beide Modelle kombiniert, hebt Teilnahmedefizite hervor und betont die Bedeutung des Engagements lokaler Interessengruppen und natürlicher Anreize für eine effektive Umsetzung. Dieser kombinierte Ansatz deutet darauf hin, dass eine adaptive Governance, die auf lokale Kontexte abgestimmt ist, ein inklusiveres und effektiveres Grundwassermanagement fördern kann, das letztendlich die Nachhaltigkeit des MDV unterstützt.

Zusammenfassend unterstreicht diese Dissertation das Potenzial, durch die Anerkennung unterschiedlicher Wahrnehmungen die Kommunikation der Interessengruppen im MDV zu fördern. Sie plädiert dafür, Machtstrukturen in Lern- und Wissensaustauschprozesse einzubeziehen. Der ESS-Ansatz bietet ein umfassendes Verständnis für das Zusammenspiel zwischen menschlichen Aktivitäten und Wasserdynamiken im MDV. Er verdeutlicht die Herausforderungen und Konsequenzen, denen Kleinbauern in ariden Regionen gegenüberstehen, und setzt sich für gezielte Anreize zur Verbesserung des Wassermanagements ein. Während institutionelle Vielfalt in der Grundwasserbewirtschaftung wertvoll ist, deutet diese Forschung darauf hin, dass letztlich ein kohärentes System erforderlich sein könnte, um die Bemühungen effektiv zu koordinieren. Der Aquiferkontrakt in Faija wird als vielversprechendes Modell identifiziert, benötigt jedoch weitere Anpassungen zur Optimierung seiner Wirksamkeit. Vergangene Erfahrungen der marokkanischen Regierung mit Aquiferkontrakten betonen diese Notwendigkeit deutlich. Hier kommt den Anreizen eine entscheidende Rolle zu, Verhaltensänderungen und Regelkonformität in wasserarmen Gebieten zu fördern, wobei eine sozial-ökologische Perspektive für eine ganzheitliche Analyse berücksichtigt wird. Letztlich hinterfragt diese Forschung konventionelle Wassermanagementpraktiken und fördert nuanciertere, inklusivere und effektivere Governance-Strategien. Durch den Beitrag zur globalen Diskussion über die Bewertung von Wasser-ESS zielt sie darauf ab, eine nachhaltige und kontinuierliche Versorgung mit wesentlichen Ökosystemdienstleistungen sicherzustellen und das menschliche Wohlbefinden in wasserarmen Regionen zu verbessern.

Résumé

La relation entre le bien-être humain et l'eau est cruciale, car l'eau fournit des ressources nécessaires, régule l'environnement et préserve la signification culturelle. Dans la vallée du Moyen Drâa (MDV) au Maroc, les conditions arides exacerbent la détérioration des écosystèmes aquatiques en raison des extrêmes climatiques et de l'agriculture intensive, posant des défis écologiques et sociaux. Les interventions humaines priorisent souvent les besoins immédiats comme l'eau potable et l'irrigation au détriment d'autres services. La répartition de l'eau douce, en particulier des eaux souterraines, est complexifiée par la surexploitation et l'épuisement récents de la nappe phréatique. Dans la MDV au sud-est du Maroc, le défi de l'équilibre entre la répartition de l'eau douce pour les oasis et le maintien des services essentiels est évident. Cette thèse vise à contribuer à ce débat en appliquant de manière pratique le concept des services écosystémiques (ESS) dans le cadre d'un système socio-écologique (SES), en se concentrant sur les interactions entre l'homme et l'eau. Elle a pour objectif d'identifier les ESS liés à l'eau fournis aux oasis du MDV, d'évaluer les perceptions des parties prenantes et de formuler des recommandations pour les stratégies de répartition de l'eau. De plus, en mettant l'accent sur l'identité du MDV en tant que région agricole irriguée, la recherche estime la valeur de l'eau d'irrigation de surface pour les agriculteurs, en reflétant les pertes subies lors du passage de l'utilisation de l'eau de surface à l'eau souterraine, en utilisant l'approche des coûts de remplacement (RCA). La présente thèse examine également en partie les connexions potentielles entre la qualité de l'eau mesurée, la santé écologique et le niveau de satisfaction des communautés locales dans différentes zones du bassin de la rivière Drâa. En outre, les opportunités et les défis de la gouvernance des eaux souterraines dans différents SES sont explorés, afin de mettre en lumière le comportement des utilisateurs et le respect des règlements sur l'utilisation de l'eau, en insistant sur les mécanismes d'incitation pour une utilisation durable. La recherche repose sur des méthodes de recherche qualitative et quantitative sur le terrain, utilisant des entretiens semi-structurés et standardisés, des discussions de groupes de discussion et des observations, qui sont ensuite transcrits et analysés à l'aide de l'analyse de contenu et de statistiques.

Le chapitre 2 révèle les priorités communes et les différences dans les perceptions des services écosystémiques (ESS) liés à l'eau entre les acteurs gouvernementaux et les habitants locaux de la vallée du Moyen Drâa (MDV) au Maroc. Les deux groupes priorisent l'eau potable et l'irrigation, mais les fonctionnaires gouvernementaux négligent souvent les services de régulation et les services culturels. Cela suggère la nécessité d'un meilleur dialogue entre les parties prenantes et une prise en compte des dynamiques de pouvoir et des structures de gouvernance. Les habitants se concentrent principalement sur la sécurisation d'une quantité d'eau adéquate pour l'agriculture et recourent souvent à des sources alternatives lorsque l'eau de surface est insuffisante. En se basant sur cela, les tests de l'approche des coûts de remplacement (RCA) au chapitre 3 révèlent les coûts variés auxquels les agriculteurs sont confrontés, les grandes exploitations bénéficiant d'économies d'échelle, ce qui souligne la nécessité de programmes gouvernementaux ciblés pour soutenir les petits exploitants agricoles. Ici, la RCA est un outil précieux pour comprendre le comportement des agriculteurs et leur prise de décision face à la rareté de l'eau et aux sécheresses, tout en reconnaissant la limitation due à l'absence de données sur les pertes non récupérées et à plusieurs facteurs déterminants et motivant le forage de puits qui peuvent ne pas être directement liés à la perte d'eau de surface. Cela souligne la nécessité de recherches futures pour affiner ces estimations et comprendre pleinement les impacts de la rareté de l'eau dans la MDV en tenant compte de toutes les variables possibles. L'analyse de l'impact de la qualité de l'eau sur les écosystèmes et le bien-

être humain montre des effets directs et indirects, tels que la détresse émotionnelle causée par l'eau salée de la rivière, comme exposé au chapitre 4. Il conclut qu'établir un lien définitif entre l'état de l'écosystème et le bien-être humain reste complexe, ce qui indique la nécessité de sondages exhaustifs pour capturer ces interactions plus précisément. À ce stade de la recherche, il devient évident que les eaux souterraines sont la principale source d'irrigation dans les systèmes socio-écologiques de la MDV, et que leur utilisation et exploitation actuelles nécessitent une action immédiate. Ensuite, l'analyse des systèmes de gouvernance des eaux souterraines, menée au chapitre 5, révèle les avantages et les inconvénients des modèles hiérarchiques et d'autogestion actuels identifiés à travers trois études de cas dans la MDV. L'analyse de l'adéquation des incitations des règles et des lois de gouvernance montre que le modèle hiérarchique a du mal à faire respecter les règles en raison des divergences entre les réglementations de l'État et les réalités locales, ainsi que des mécanismes de sanction faibles, ce qui réduit drastiquement l'efficacité des incitations. En revanche, l'autogestion, observée à M'hamid et Faija, démontre des taux de conformité plus élevés grâce à des communautés d'utilisateurs bien définies qui conviennent mutuellement de réglementer l'utilisation des ressources. Le contrat d'aquifère à Faija, situé dans les extensions des oasis et qui combine les deux modèles, met en évidence des insuffisances de participation, soulignant l'importance de l'engagement des parties prenantes locales et des incitations naturelles pour une mise en œuvre efficace. Cette approche combinée suggère qu'une gouvernance adaptative, alignée sur les contextes locaux, peut favoriser une gestion des eaux souterraines plus inclusive et efficace, soutenant ainsi la durabilité de la MDV.

En résumé, cette thèse souligne le potentiel de reconnaissance des perceptions diverses pour favoriser la communication entre les parties prenantes dans le MDV. Elle plaide pour la prise en compte des dynamiques de pouvoir dans les processus d'apprentissage et d'échange de connaissances. L'approche ESS offre une compréhension globale de l'interaction entre les activités humaines et les dynamiques de l'eau dans le MDV. Elle démontre les défis et les conséquences auxquels sont confrontées les petites exploitations agricoles dans les régions arides et plaide pour des incitations ciblées pour améliorer la gestion des ressources en eau. Bien que la diversité institutionnelle dans la gouvernance des eaux souterraines soit précieuse, cette recherche suggère qu'un système cohérent pourrait finalement être nécessaire pour coordonner efficacement les efforts. Le contrat d'aquifère à Faija est identifié comme un modèle prometteur, mais nécessite des ajustements supplémentaires pour optimiser son efficacité. Les expériences passées du gouvernement marocain avec les contrats d'aquifères soulignent clairement cette nécessité. Les incitations jouent ici un rôle crucial pour provoquer des changements de comportement et assurer le respect des règles dans les zones en stress hydrique, en tenant compte d'une perception socio-écologique pour une analyse holistique. Finalement, cette recherche remet en question les pratiques conventionnelles de gestion de l'eau et promeut des stratégies de gouvernance plus nuancées, inclusives et efficaces. En contribuant à la discussion mondiale sur l'évaluation des ESS liées à l'eau, elle vise à garantir une fourniture durable et continue de services écosystémiques essentiels, améliorant le bien-être humain dans les régions souffrant de pénurie d'eau.

List of Figures

List of Tables

List of Equation

List of Appendix

Chapter 1

Introduction

"No matter who we are, or where we live, our well-being depends on the way the ecosystem works" (Haines-Young and Potschin 2010). Ecosystems provide us with "provisioning" ecosystem services (ESS), such as water and food, essential for our daily lives as inputs for our productive activities (Daily 1997; MEA 2005). They also play a crucial role in regulating the environments in which we live, known as "regulating" services (MEA 2005), and contribute to our spiritual well-being through their "cultural" significance or the opportunities they provide for recreation or the enjoyment of nature (MEA 2005; Costanza et al. 2017; Haines-Young and Potschin 2010). ESS impact human well-being and all its components, including basic material needs such as food and shelter, individual health, security, good social relations, and freedom of choice and action. However, the demand for these services is increasing, while many of the world's water ecosystems are in serious decline, putting the supply of critical ESS at risk. In natural resource management, an important and yet challenging question is how best to manage ecosystems to maximize the overall productivity of ESS and ensure their long-term contributions to human well-being, particularly in freshwater ecosystems (Smith et al. 2016).

In the arid and semi-arid regions of the Mediterranean, such as Morocco, water management and the supply of essential ecosystem services face numerous challenges. The increasing demand for freshwater poses a critical threat to the limited capacity of water systems to meet various needs (Mahmoudi, Al-Barrak, and Massoud 2011). The frequency and intensity of extreme climate events globally, such as floods and droughts, have risen in these areas, with projections indicating further increase (Bates, Kundzewicz, and Wu 2008; Capon et al. 2013; Wang et al. 2017; C. Yu et al. 2018; Han et al. 2019). These events put immense pressure on water resources, affecting the structure, composition, and function of water ecosystems and disrupting the supply capacity of ESS and sustainable development of the social economy (Jentsch and Beierkuhnlein 2008). The significance of freshwater within the hydrological cycle is evident through its critical role in domestic, irrigation, and other uses such as sustaining inland water ecosystems like rivers, lakes, and wetlands (Aylward et al. 2005). These ecosystems offer essential services beyond the obvious, including recreational opportunities, scenic beauty, and the preservation of biodiversity. Climate-induced alterations in these ecosystems could weaken spiritual connections tied to sacred elements, impacting societal values (MEA 2005). Agricultural growth, the primary use of freshwater in most arid regions, has led to much of the ecosystem degradation observed (Salmon et al., 2015). Increased agricultural production in arid areas has been achieved through both intensification and expansion of agriculture, contributing to the loss of other provisioning, regulating, and cultural services (Martin-Ortega 2015). Salinization of freshwater has become a visible impact on farmland surfaces and water tables due to overexploitation. This overexploitation occurs through intensive farming practices, characterized by the use of high-yielding crop varieties and increased inputs like fertilizers and pesticides. Additionally, there may be a greater demand for water for cooling infrastructure in response to warming (Y. Yu and De Dear 2022).

Extensive anthropogenic changes to the world's ecosystems increase the likelihood of large, nonlinear, and irreversible changes (IPCC, 2007). Humans have altered natural water ecosystems to enhance their productive capacity (Bennet et al., 2005). The capacity of an ecosystem or a social-ecological system (SES) to sustain a desired set of ESS in the face of ongoing evolution and change (Biggs et al., 2012) is referred to as resilience (Biggs et al., 2012). In arid regions, human alterations are primarily characterized by water resource development, such as the construction of dams, irrigation networks, and drinking water supply systems, which have rapidly replaced natural systems with human-engineered ones to meet human demands (Aylward et al., 2005; Vörösmarty et al., 2010; Russi et al., 2013; Raymond et al., 2013; Martin-Ortega et al., 2015; Biggs et al., 2012). These developed systems have typically been designed solely for major human consumptive uses (e.g. irrigation or drinking) or non-consumptive uses (e.g. hydropower). Large dams, for instance, have significantly increased the availability of freshwater provision services but have also come at a cost (World Commission on Dams 2000). Modifying ecosystems often degrades the resilience of ESs, especially the less obvious services essential for human well-being (Martin-Ortega 2015), and compromises freshwater quality, impacting both human health and biodiversity.

Within SES, ecosystem services are interrelated and can interact in complex and unexpected ways (Bennett et al., 2009). The finite nature of freshwater poses a challenge in distributing it to optimize all the services it can provide. Because different sectors of society often value, need, and demand different ESS, decisions about which ecosystem services to sustain are inherently political (Robards et al., 2011). Every SES produces a variety of interacting ES at multiple scales, and it is not possible to increase the resilience of all ESS simultaneously (MEA, 2005; Raudsepp-Hearne et al., 2010). Decisions about this environmental asset often ignore the crucial trade-offs among these services(Rodríguez et al. 2006). This is the lesson of the environmental impacts observed across the world from water resource development (Šteflová et al. 2022). These trade-offs are prominent among provisioning and the rest of the services (Rodríguez-Ortega et al. 2014). In arid regions, the priority given to provisioning services, particularly drinking water and irrigation, often overshadows considerations for regulating or cultural services due to water scarcity. As a consequence of this disregard, the regulating or cultural services are often weakly supplied or in some cases lost, leading to feedback loops wherein ecosystem degradation cascades back and reduces human well-being (Ruskule et al., 2018). Diverse stakeholders hold varying perceptions regarding these services, leading to trade-offs in their water services usage and valuation (Cavender-Bares et al. 2015). Overlooking the interconnectedness between water ESS and society's overall reliance upon their supply threatens the sustainability, local livelihoods, and overall success of their development decision-making (Pagiola et al., 2004).

Due to growing pressure and increasing competition among various water users for surface water resources, reliance on groundwater resources has significantly increase d. In arid regions, intensive aquifer development is common due to the accessibility, affordability, and reliability of groundwater. However, managing groundwater poses several challenges. First, groundwater exhibits characteristics of a common pool resource, making it difficult to prevent over-abstraction. Aquifers are large enough that excluding potential beneficiaries from using the resource is costly, if not possible. The extraction of a unit of the resource by one user prevents access to a unit of the resource from others, making sustainable management difficult and creating room for conflicts (Gardner et al., 1997; Baldwin et al. 2018; Gorelick and Zheng 2015). Second, the costly and complex nature of generating knowledge about aquifers hampers effective monitoring and management strategies. Hydrogeological knowledge is often fragmented, making it difficult to obtain a comprehensive understanding of aquifers (Comte et al., 2017). Understanding and defining the boundaries of aquifers is complex due to hydrogeological dynamics and socio-political factors. Together with the lack of long-term monitoring infrastructure, significant challenges are facing aquifer management (Ross, 2022). Additionally, the characteristics of aquifers vary from one location to another, making it challenging to apply one-size-fits-all approaches to aquifer management. Furthermore, groundwater systems are social-ecological systems, where anthropogenic activities and groundwater conditions are linked through dynamic, non-linear processes (Cullet 2006; Ghosh and Kansal 2019; Bouchet et al., 2019; Schütze et al. 2020). Sustainable solutions that consider socio-economic values and ecological aspects of groundwater and dependent ecosystems are needed (Huggins et al., 2023). Proposed solutions to this groundwater dilemma include nonmarket, bottom-up resource sharing by communities that benefit from collective use via cooperation (Ostrom, 1992). The literature also advocates for cooperation and co-management approaches between the state and local communities, when making decisions about groundwater resources, to balance the interests of individual users with the collective need for sustainable groundwater management (Asprilla-Echeverria 2021).

Addressing the multifaceted challenges outlined earlier underscores the overarching goal of optimizing freshwater ecosystem services supply. The complex interplay between human well-being and water systems in arid regions emphasizes the need for wise water resource management (Redpath et al., 2013; Madden and McQuinn, 2014; Farrokhzadeh et al., 2020). It requires a nuanced understanding of the human-nature relationship and acknowledging the diverse range of water uses and benefits, and of these, which are most critical and for whom, especially considering the uneven water supply distribution. Achieving this objective involves reconciling the competing demands and priorities of various stakeholders and sectors within the water system and designing adequate institutional frameworks and regulations for allocating such resources.

In the arid Middle Drâa Valley (MDV) in southern Morocco, the challenges of allocating freshwater for the oases along the Drâa River, overexploitation of aquifers, and maintaining crucial services for the local population are evident. The MDV, characterized by water scarcity and new governance challenges, provides the perfect example of the interconnectedness of humans and nature and their impact on well-being and ecosystems. With this context in mind, the research questions are outlined in the following section.

1.1. Main Research Questions and Objectives

Drawing on the social-ecological systems (SES) perspective, this dissertation begins with the fundamental concept of Ecosystem Services (ESS) (MEA, 2015), rooted in the field of environmental economics. This perspective serves as a theoretical foundation and a key tool to analyze, understand, and interpret the complex challenges of water decision-making in the MDV, especially in the face of worsening climatic conditions. Recurring droughts, affecting both surface and groundwater availability in the MDV, indicate potential future crises and underscore the vulnerability of water resources and essential ecosystem services crucial for local livelihoods. The urgency of these issues underscores the importance of exploring the specific challenges impacting water-related policymaking, with the goal of not only unraveling the complexities but also formulating recommendations to sustain the current and future supply of vital water ecosystem services in the MDV.

To gain a more intricate understanding, this research delves into the concept of ecosystem services (ESs) within the complex SES of the MDV. The investigation seeks a profound understanding of the dynamic interplay among diverse elements that shape the MDV's SES. This system, characterized by interconnected variables, encompasses climate nuances, land use dynamics, socio-economic conditions of local communities, water quality and quantity, water management practices, local and regional institutions, and geographical aspects of the oases, among other factors. By centering water ESS at the core of this research, the main aim is to scrutinize the impact of existing water allocation practices on the ESS within the MDV. A pivotal starting point involves understanding the utilization of various water sources, including both surface and groundwater. This understanding extends to exploring the spectrum of water ESS, encompassing provisioning, cultural, and regulating services. The research delves into the perspective of the local inhabitants regarding these services, investigating their awareness and perception of the services they perceive, and examining their view on the state of these vital ecological contributions. To ensure a thorough comprehension, the inquiry extends to also include regional governmental actors responsible for surface water allocation. The objective is to compare and analyze these contrasting perspectives, identifying similarities and differences, with the ultimate goal of generating practical applications and deriving recommendations for water allocation strategies in the MDV. With a keen eye on the MDV’s identity as an irrigated farming region, the focus sharpens on the farmers and their socio-economic use of irrigation water sources. This focus is essential to gain detailed insights into the diversity of factors such as droughts and water scarcity and their effect on irrigation services, crop production, and the unique character of oasis farms. This focused view also aims to understand the farmers' experiences, including their benefits and losses, in the context of water scarcity and their diverse adaptation processes to maintain irrigation water-ESS, using an economic valuation lens. The present analysis intends to demonstrate how the economic valuation of ESS contributes to generating knowledge that can guide regional water-related decision-making. Additionally, we thoroughly explore the advantages, challenges, and limitations associated with such approaches.

Groundwater resources in the MDV have been heavily exploited for irrigation purposes in the last decade, which is visible within and in the extension areas outside of the traditional oases. In this sense, the aim is to explore groundwater governance in the MDV, its opportunities, and challenges. This exploration delves into the processes shaping groundwater governance, unveiling their occurrences and how they're shaped by the biophysical, economic, and social characteristics of selected aquifer systems and the communities interacting within and beyond the oases. Here, groundwater is addressed as a component of complex social-ecological systems where the biophysical characteristics and processes of the environment intertwine with the social, political, and economic systems (Swyngedouw, 1999; Ostrom, 2009; Linton & Budds, 2013; Barreteau et al., 2016; French, 2018; Huggins et al., 2023). This investigation is done using an environmental policy analysis and economics lens which places high emphasis on incentive-based mechanisms to promote sustainable resource use, under the premise that they might have the potential to influence the behavioral patterns of users toward environmentally friendlier directions (e.g. WCED, 1987; Turner & Opschoor, 1994; Shapiro & Glicksman, 2000; Hahn, 2000; Kraft, 2021). It pays particular focus on the assessment and comprehension of factors influencing rule compliance among groundwater users and critically analyzes the adequacy of incentives proposed within regulations to influence water users’ practices towards sustainability. In this sense, this research aims at answering the following questions:

- **How can the concept of ESS contribute to understanding human-water relations in an arid context?**
- **How can the monetary valuation of ESS be used to inform local water decision-making processes? What are the advantages and limitations of these approaches?**
- **What are the opportunities and challenges that groundwater governance faces in the MDV to sustain the supply of water-related ESS?**

The following sections delve into the foundational literature that supports this dissertation, introduce the research region, outline the methodology employed, and present the structure of the dissertation.

1.2. Conceptual Approach

To address the research questions formulated earlier, this dissertation falls into the field of "interdisciplinarity", blending theories and concepts from environmental economics, social, ecological, and policy analysis sciences within the context of the SES literature. This section provides an overview of the conceptual approach taken in this dissertation. The individual chapters that follow draw on specific concepts, with not all concepts playing a role in every chapter.

1.2.1. The Concept of Ecosystem Services: Origin, Utility, and Assessment Approaches

In the realm of natural resource management, the concept of ESS represents a shifting paradigm in understanding and conceptualizing the intricate relationship between humans and nature (Raymond et al., 2013). This concept can be traced back to the late 1960s, with significant contributions from scholars such as King (1966), Helliwell (1969), the Study of Critical Environmental Problems (1970), and Odum & Odum (1972). Initially, the development of the ESS concept focused on how human needs and well-being are intertwined with the quantities and qualities of the finite natural resource base, and the reciprocal impacts of environmental changes on human activities, and vice versa. In a social-ecological system, the well-being of human populations is closely linked to the availability and quality of these services. Functional ecosystems provide essential resources and life-supporting processes that directly impact human health, economic stability, and overall quality of life (Gergen, 2009; Delgado et al., 2019; Andrews and Duff, 2020; Devooght et al., 2023). The Millennium Ecosystem Assessment (MEA), initiated by the United Nations in 2000, aimed to assess how ecosystem changes affect human well-being. A key contribution of this initiative was the introduction of ESs, emphasizing the crucial integration of these services in decision-making processes to counteract ecosystem deterioration. In its publications (MEA, 2003, 2005), the MEA defined ecosystems as dynamic complexes of interacting elements, highlighting ESS as the benefits humans derive from these interactions. This thesis adopts this understanding of ESS. Subsequent initiatives, such as The Economics of Ecosystem Services and Biodiversity (Kumar, 2010) and national-level assessments like the UK National Ecosystem Assessment (2011) and the Spanish Millennium Ecosystem Assessment (EME, 2011) have followed.

These initiatives incorporated the notion of "final service", which considers services as the end products of nature, distinguishing them from intermediate natural components and benefits (Boyd and Banzhaf, 2007). The focus on final ecosystem services aims to prevent double counting when valuing ecosystem services (Lele, 2009). The author emphasizes that the 'process' should not be the focus of valuation; rather, it is the outcome of the process (the final service), that impacts human well-being and, therefore, holds economic value. This dissertation adopts the notion of "final service". According to Fu et al. (2011), excluding intermediate services from economic valuation does not imply that they have no value, but rather that their values are realized through the value of the final ecosystem services. The Common International Classification of Ecosystem Services also recognizes the need to differentiate between final ESS and ecosystem goods and benefits (referred to as 'products') and defines ESS as the contributions that ecosystems make to human well-being (CICES, 2012). A fundamental characteristic is that final services maintain a connection with the underlying ecosystem functions, processes, and structures that generate them. Based on this, a classification for ESS was developed in 2009, with provisioning, cultural, and regulating services as the main categories. A CICES version updated in 2018[1] serves as the foundation for part of the ESS assessment in the present research due to its hierarchical structure and detailed classification of services categories.

Further, a discussion among scholars has developed around the value of ESS. In environmental economics, the predominant paradigm for interpreting the value of these services has been neoclassical economics (Gomez-Baggethun et al. 2010). Within this paradigm, the value of ecosystem services is measured in terms of welfare change associated with changes in ecosystem status in monetary units, as discussed in this dissertation (Pearce & Turner 1989). Scholars have distinguished between 'direct use values' which include consumptive use (e.g. food, fuel); productive use (e.g. construction materials); and other uses (e.g. recreation, education), as well as 'indirect use value' such as climate regulation, maintenance of soil fertility, and cleansing of water and air (Barbier et al., 2009). Even if an ecosystem has no current use, it may have an option value, for instance, the future may bring agricultural pests which are still unknown today and will need to be controlled biologically (Heal et al., 2005). The same authors identified non-use values including bequest value: driven by people's willingness to pay to ensure that people in the present or the future benefit from something in the ecosystem; and existence value: originally defined as people's willingness to pay to ensure the continued existence of a service without any actual or potential use in the future (Kurtilla, 1967; Waston et al., 1995). In chapter 3 of this dissertation, the focus is on the direct use value of irrigation water.

The number of methods developed for assessing and valuing ecosystem services in specific situations is increasing (Bagstad et al., 2013). When ecosystem goods are traded in markets (e.g., timber), the market price (e.g., dollars/cubic meter) is a measure of the benefits people get from a unit of the good. However, since most ESS are not traded in markets, and do not have observable prices, economists estimate the value of changes in ESS by leveraging the information conveyed by individuals' observable decisions (Binder et al., 2017). There are *sociocultural methods* for understanding preferences or social values for ecosystem services, such as deliberative valuation methods (e.g., Kelemen et al., 2013, Pereira et al., 2005), preference ranking methods (e.g. Calvet-Mir et al., 2012), and multi-criteria analysis methods. There are also *monetary techniques* for estimating the economic values of services, such as stated preference methods (Bateman et al., 2002) using contingent valuation (e.g. Gürlük 2006) and choice experiments (e.g. García-Llorente et al. 2012b); revealed preference methods through the use of the travel cost method (e.g. Langemeyer et al., 2015, Martín-López et al., 2009) or hedonic pricing methods (e.g. Gibbons et al., 2014); and cost-based methods such as the replacement cost approach and defensive expenditure method (e.g.

[1] CICES - https://cices.eu/

Shuang et al., 2010; Sundberg, 2004b). The selection of a particular method to apply in a specific case can depend on many factors, including the ecosystem services at stake, the strengths and limitations of different methods, and available data, resources, and expertise (Harrison et al., 2018). This dissertation focuses on monetary techniques for valuing ecosystem services (ESS) and specifically demonstrates and tests the replacement cost approach (RCA), a cost-based method where the loss of a natural system service is assessed by estimating the cost required to replace that service. In Chapter 3 of this research, the utility and rationale behind the selection of this evaluation method are explained. Within this process, both the inherent advantages and limitations of such a technique are acknowledged. A significant facet of this research involves exploring elements that might need refinement or inclusion to accurately estimate the true worth of this valuation. The endeavor is not solely about valuation but also about a comprehensive examination that embraces a critical discourse on the very nature of quantifying the value of one of the key ESS.

Broadly, the ecosystem services-based approach is one way to understand the complex relationships between nature and humans to support decision-making, reverse the declining status of ecosystems, and ensure the sustainable use and conservation of resources. According to Martin-Ortega et al. (2015), this approach entails four core elements. The first element involves focusing on the status of ecosystems and their effects on human well-being, recognizing that humans assign value to different aspects of ecosystems. The second element includes understanding and describing the ecosystem in terms of its biophysical structure, processes, and functions, which lead to the delivery of services to humans. This element is partly addressed in Chapter 4 of this dissertation. The third element involves integrating natural and social sciences along with other strands of knowledge for a comprehensive understanding of the service delivery process. By definition, this approach is transdisciplinary (Martin-Ortega et al., 2015), as demonstrated in Chapters 4 and 5 of this research. It also requires considering non-academic knowledge, including the views and perceptions of stakeholders at relevant scales. This dissertation extensively integrates and relies on these perspectives to enrich its foundation. The fourth and final element of this approach involves assessing the services provided by the ecosystem for their incorporation into decision-making. This inherently implies a qualitative or quantitative assessment of the services delivered by ecosystems and the identification of their social or individual values in monetary and/or non-monetary terms. The ES approach discussed in this dissertation is built on the four core elements discussed above.

1.2.2. A social-ecological conception of ecosystem services' resilience

Resilience is a perspective for analyzing SES that emphasizes the need to understand and manage change, particularly unexpected change (Maciejewski et al., 2015; Sarkki et al., 2017; De Luca et al., 2021). In Chapter 2, this dissertation partly relies on the conception of Biggs et al., (2012, 2015) from the Resilience Alliance[2], focusing on understanding and managing shifts in SES to support ESS resilience. They define SES resilience as the ability to maintain the delivery of essential services despite sudden shocks or ongoing transformations. The same authors consider SES as complex adaptive systems that can self-organize and adapt in response to internal or external disturbances and changing conditions, characterized by non-linear dynamics (Folke 2006; Levin et al., 2013). This perspective views change as a constant, offering

[2] Stockholm Resilience Center: https://www.stockholmresilience.org/

opportunities for improvement. Biggs et al. (2015) outlined seven key principles to strengthen SES's capacity to sustain desired services, supported by critical evidence analysis. Biggs' (2012) analysis was explicit about the challenges of the Anthropocene, with human well-being and ESS trade-offs occurring across spatial and temporal scales, co-produced by SES, and accounting for issues of power and equity. These principles are: (P1) maintain diversity and redundancy; (P2) manage connectivity; (P3) manage slow variables and feedback; (P4) foster Complex Adaptive System thinking; (P5) encourage learning and experimentation; (P6) broader participation and (P7) promote polycentric governance systems. Biggs's approach delves into applying these generic principles and highlights additional research requirements concerning the management and governance of ESS for human well-being. This approach significantly drew the focus of this dissertation towards aligning the analysis of ESS in Chapter 2 and the insights gathered on two of the key principles, P5 and P6. This is done with the belief that assessing ESS could foster learning opportunities among stakeholders within an SES and encourage broader participation of diverse stakeholders, each bringing unique perspectives and knowledge. Such assessments could profoundly impact decision-making processes across various levels. However, while recognizing the potential benefits, this dissertation maintains a critical stance toward this process, acknowledging the complexities and potential limitations in effectively integrating diverse stakeholder perspectives into decision-making frameworks and motivating broader participation.

1.2.3. The incentive adequacy analysis in SES

Governance can be defined as how communities, societies, and organizations organize themselves to make decisions about important issues (Armitage et al., 2017). This dissertation explores this concept with a focus on groundwater governance. The latter faces significant challenges due to the open-access nature of aquifers, leading to overexploitation and conflicts among users seeking personal benefits (Holt et al., 2012). Even in instances where groundwater is considered a public good, lingering perceptions of it being "private" can hinder "rule compliance" and drive overexploitation (Mechlem, 2016). Regulatory frameworks are crucial in groundwater governance, especially as these resources are increasingly depleted and polluted, leading to environmental concerns (Mechlem, 2016). Natural resource economics offers solutions by examining consumption choices, depletion rates, intertemporal effects, and optimal conservation policies based on natural conditions and technological capabilities (Maldonado, 2008). Public sector economics addresses how states can use instruments like fines, taxes, subventions, and regulations to motivate efficient natural resource use (Stiglitz, 2015). This relates to the rise of "*incentive-based regulations and policies*" as a response to environmental concerns and compliance challenges with groundwater use regulations (Kerr et al., 2012; Rapoport et al., 2001; H. Travers et al., 2011; Vatn, 2009). Economists analyze incentives embedded in regulations and policies to understand factors influencing rule compliance among water users. This approach operates under the assumption that the proposed incentives may or may not align effectively with the intended goals of the policy or regulations, which is addressed in Chapter 5 of this dissertation. "Incentives" are mechanisms designed to guide behavior toward responsible resource use and compliance with regulations to achieve public policy goals (Kerr et al., 2012). They typically fall into financial and non-financial categories (Neeman, 1999; Delmas and Keller, 2005; Delmas and Montes, 2007; Nordhaus 2015), further explained in Chapter 5 of this dissertation. Using the SES framework, groundwater use regulations are evaluated across three governance systems focusing on incentives and their effectiveness. "Adequacy" refers to how well the incentives shape user behavior as intended, considering the interests, objectives, and conditions of the actors concerned. The goal is to align individual and collective behaviors with water conservation goals (Wight et al., 2021).

1.3. The Research Area

1.3.1. Topography and climate

The fieldwork for this dissertation was conducted between 2020 and 2023 in the Drâa river basin, located in the south of Morocco (Figure 1.1). The description of the research area in this section is based on observations made in the field as well as other scientific contributions to the area.

The Drâa River Basin is situated in south-eastern Morocco and covers an area of almost 115,000 km^2, stretching from the High Atlas Mountains to the Atlantic Ocean in the west and to the Sahara Desert in the south (Carrillo-Rivera et al., 2013). The upper and middle Drâa sub-basins are more densely populated, with 600,000 inhabitants engaged in agriculture and tourism-related economic activities (HCP, 2015). The lower Drâa provinces are less populated. The two major cities in the basin are Ouarzazate, located upstream with a population of 71,067 inhabitants (HCP, 2015), and Zagora, situated in the middle of the basin with 40,067 inhabitants (HCP, 2015). Topographically, the region is divided into several units, including valleys, mountains, plains, and desert plateaus. This division offers diverse possibilities for varied and complementary use of the natural environment. Along the MDV, a series of six oases spans over 26,000 ha (Mezguita, Tinzouline, Ternata, Fezouta, Ktaoua*,* and M'hamid from north to south), displaying an unusual greenness in this pre-Saharan environment. Cultivation in these oases heavily relies on external water sources such as rain and snowmelt. The other topographical compartments, mountains, plains, and desert plateaus, are primarily used for pastoral purposes by sedentary and nomadic herds. The average annual rainfall is very low, decreasing from north to south: 108 mm at Agdz and 74 mm at Zagora. Since the late 1970s, the frequency of drought years has increased in Northwest and West Africa, posing a significant challenge to the future development of these regions. According to the Intergovernmental Panel on Climate Change (IPCC) conventions, a general decrease in rainfall and increased surface heating are expected for sub-Saharan Africa and north of the Sahara until 2050, leading to further reductions in freshwater availability (Klose, 2008). The hot and dry southern and eastern winds originating in the Sahara Desert negatively impact agriculture in the region and the overall well-being of the local population (Moumane, 2022).

1.3.2. Water resources and agriculture in the Middle Drâa Valley

The Drâa River's hydrographic network, organized around the Oued Draa, is characterized by the irregularity of its contributions and the discontinuity of its flow (Province de Zagora, 2015). The river drains large volumes of water from the High Atlas, with an average annual inflow of 560 million m^3 ranging from 90 to 1400 million m^3 (Province de Zagora, 2015). After the construction of the El Mansour Eddahbi reservoir in 1972, surface water distribution for the oases has been managed by periodic releases (Höllermann, 2016). The El Mansour Eddahbi dam and the newly operational Agdz dam (since 2023) play crucial roles in supplying water to cities upstream and the oases along the MDV. This water serves both agricultural and domestic needs in the region, with a combined average annual release of 120 million cubic meters (Moumane, 2022). These dams effectively regulate water flow to the MDV oases, which rely on the underlying alluvial aquifers for replenishment, primarily from dam releases (Klose et al., 2010).

However, during periods of drought or insufficient dam filling, farmers in the southern regions endure reduced and less predictable water supplies from these releases. In each oasis, water releases are still managed by traditional and local institutions to secure and allocate water to most of the local inhabitants in need of water. The number and volume of releases depend on the volume of stored water in the reservoir each year (e.g. in humid years 7 releases, while during dry periods 3 or 4 releases) (ORMVAO, 1995). Yet, this amount of water is not sufficient to meet the irrigation needs of farmers in the valley, who primarily rely on groundwater between dam releases to grow household vegetables and maintain the oases' palms (Fico, 2021). During the summer of 2021, the lack of rain and surface water led to a major drought in the valley, with many farmers in the oases unable to keep their palms watered. The rate of salinity increases from upstream to downstream and varies from 2 to 9 g/l (Province de Zagora, 2015). Groundwater resources are limited and are mainly found in fractured zones and alluvial zones. The productivity is very low, ranging from 0.1 to 100 m³/day. In years of droughts, most of the wells dry up. The severe droughts are causing overexploitation and depletion of most aquifers in the area.

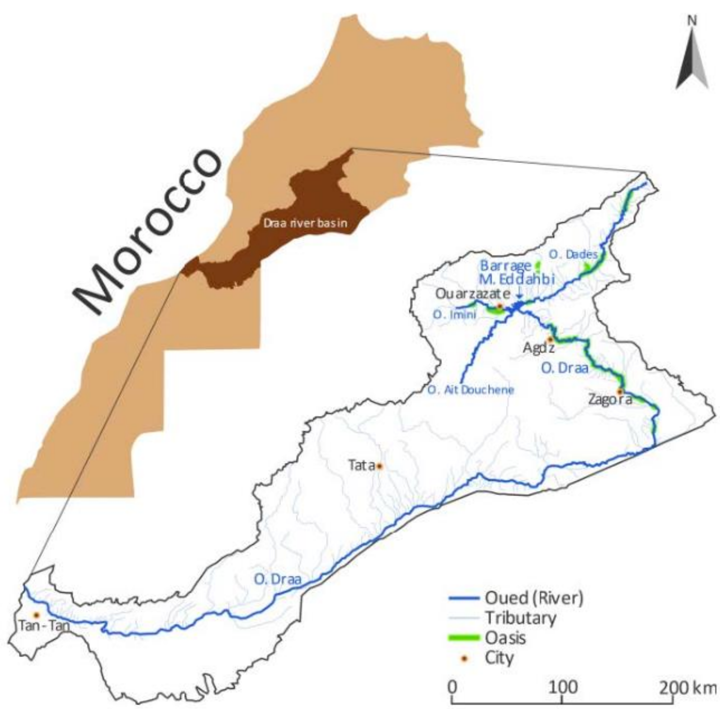

Figure 1.1. Course and location of the Drâa River (*Source: SALIDRAA 2*).

These water sources as a provisioning service, also contribute to many other ecosystem services (i.e. regulating and cultural services) that impact directly and indirectly on the local populations' well-being. It also plays a role in sustaining the oasis ecosystem, which provides another set of services not only for local communities to benefit from, but also for the region (e.g. recreation, tourism). Agriculture is the main economic activity in this area. Its development is hampered by several constraints, but its potential is considerable. Agricultural management units in the area, which are also affiliated with the Ministry of Agriculture, are the Regional Office of Agricultural Development (ORMVAO) in Ouarzazate, the agricultural development centers (CMVs), and the water users' associations (WUAs) located in most of the oases. Fruit growing is dominated by date palms, which are the area's main crop, renowned for its date production. However, this tree is threatened by Bayoud, which continues to devastate the palm grove (A. Saleh et al., 2015). Research work on this disease, which often affects the best varieties of date palms, has led to the selection of resistant types to be cultivated, which often cost less in the market. Droughts and water scarcity also affect the quality of these Bayoud-resistant varieties, affecting their price in the local and national markets. Other fruit species are highly diversified and fairly well-developed, particularly in the oases upstream from the Drâa Valley (e.g. Almonds, Apricots). Farming in the MDV is dominated by the production of wheat, and alfalfa, and in the last decade, the development of the culture of watermelons, mainly in the so-called Faija plain, which is one of the areas extended outside of the oases, characterized by new agricultural development (Karmaoui et al., 2016).

1.4. Methodology

1.4.1. Literature Review

For this dissertation, an extensive literature review was conducted, serving as the foundational groundwork preceding both the conceptualization and empirical undertakings within this research. This comprehensive exploration was tailored to the general aim of this dissertation and its specific objectives, notably, the conceptual approach outlined in the previous section (see section 1.3), expounded upon the following chapters. The literature was updated throughout the research duration, including ESS classification frameworks and SES frameworks, to remain current with evolving research landscapes.

1.4.2. Data collection and analysis

This research was conducted within the framework of the project SALIDRAA 2, a Moroccan-German research project funded by the German Federal Ministry of Education and Scientific Research (BMBF) for the period April 2019 to March 2025. The project aims to guide young scientists towards collaborative research work involving many different disciplines and stakeholders by combining the perspectives and knowledge of natural and social scientists working closely with local actors. This dissertation is part of a transdisciplinary and interdisciplinary vision and cooperation, to develop a socio-ecological understanding of the Drâa system and create holistic solutions for a concrete environmental problem.

The empirical data presented in this dissertation was collected through qualitative and quantitative field research based on semi-structured and structured interviews, focus group discussions, and observations. To adapt to COVID-19 travel restrictions, interviews were carried out in both physical and virtual settings. Each chapter in this dissertation aligns with specific field trips conducted between 2019 and 2023, directly tied to the corresponding chapter objectives (see section 1.1). Detailed descriptions of the research methods utilized are provided within each of the following chapters. Various semi-structured interviews were conducted with a wide range of different actors, including regional governmental officials, members of households, men and women (mostly farmers), members of NGOs, associations, and cooperatives in the MDV, as well as members and representatives of WUAs. Additionally, focus group discussions were held with members of farming households practicing agriculture in the Faija plain, as described in the previous section. These discussions aimed to create a space for farmers to openly discuss and express different opinions, contributing to a variety of viewpoints on the topic at hand.

In the framework of the SALIDRAA 2 project, a traineeship in the MDV (October 2019), a kick-off workshop in Ouarzazate (September 2019), one virtual meeting, and one in-person stakeholder meeting (February 2021 and September 2022 respectively), as well as a scenario building workshop (January 2024) were organized with government officials and local inhabitants from the region. These activities helped bring together various knowledge holders from the research area and added value by enriching the data collected for this dissertation. Observing the environment and farming activities in the oases was a crucial part of this research. Over four years, numerous field trips were conducted and the significant changes occurring in the natural and social environment of the MDV were documented. The data collected in the field was cross-referenced with the analysis of government policies, reports, and socioeconomic data provided by regional and communal actors in the area.

The gathered data undergo transcription and analysis using the software MAXQDA (VERBI Software 2020,2021). Initial code categories were formulated after a thorough review of the available data and researched frameworks (e.g., ESS classification frameworks, SES framework, incentive analysis), guiding the subsequent coding of interviews. Throughout this process, codes and sub-codes were refined or added as their relevance emerged. This dissertation integrates statistical analyses, prominently featured in Chapters 2 and 3 (e.g. correlations and regressions). Additionally, it includes an extensive qualitative analysis of the collected data, employed across chapters 2, 3, and 4.

1.5. structure of the dissertation

This dissertation consists of five additional chapters. **Chapter 2** explores the concept of ecosystem services (ESS) with a specific focus on freshwater services and their vulnerability to climatic challenges in the MDV. Using an ESS framework, the identified services were categorized and classified. Recognizing the limitations of relying on a singular set of stakeholder perspectives for effective management strategies within a Social-Ecological System (SES), this chapter aims to compare the varied ESS perceptions of two key stakeholder groups: government officials and local inhabitants. This endeavor aims to reveal the divergent values and interpretations that influence the demand and utilization of these services. The empirical insights gathered in this chapter lay the groundwork for reflecting on the resilience of water ESS, aligning with two fundamental principles. This reflection intends to provide a potential operational framework for understanding ESS, particularly through the evaluation and comparison of diverse stakeholder perceptions. Ultimately, this framework aims to contribute to a comprehensive approach to managing water ecosystem services within the arid MDV.

Chapter 3 moves forward with the economic valuation of a main provisioning ES in the research area. The focus is on the impact of water scarcity in the Middle Drâa Valley (MDV) in Morocco, a critical issue threatening the self-sufficiency of farming practices and significantly affecting agricultural production and the livelihoods of the oases' population. Assessing the economic value of ecosystem services is crucial for informed decision-making, as it can highlight the importance of these services, aiding in the prioritization of resource allocation and policy interventions. While there are various methods to do so, direct valuation methods could not be applied in this context, leading to the use of indirect revealed preference methods. Considering that well-digging may not only partially reflect the actual loss in ESS, the replacement cost approach (RCA) is employed to assess the expenses incurred by farmers in substituting surface water resources over the past two decades. The primary goal is twofold: first, to estimate the monetary value attributed to irrigation water through this replacement process, and second, to determine the minimum amount of lost ecosystem services value over this period. This chapter offers critical insights into the challenges faced by farmers in accessing water resources, providing valuable foresight into their behaviors and decision-making processes in the face of water scarcity. It also contributes to the field of ecosystem services valuation by showcasing the practical application of the RCA method in estimating the value of various lost ecosystem services, along with its advantages and limitations.

In **Chapter 4,** the focus centers on the provisioning services provided by the Drâa River basin. This study integrates human well-being concepts with assessments of the biological and physicochemical qualities of river water and explores the associations between these aspects. The chapter aims to conduct a comparative analysis of biological and physicochemical parameters across various segments of the Drâa River basin. Additionally, it seeks to compare households' perceptions regarding the quality and quantity of drinking and irrigation water in different areas of the basin. A key emphasis is placed on determining whether the measured water quality index, biological quality index, and human satisfaction index exhibit correlations. This comparative analysis aims to reveal potential connections between measured water quality, ecological health, and the satisfaction levels of local communities, providing valuable insights into the intricate relationship between ecosystem health and human well-being.

Chapter 5 focuses on groundwater as a common pool resource by exploring the complex challenges of its governance and sustainability in the MDV. This chapter analyzes the case of three aquifer systems using a multi-faceted approach that includes an SES framework and an incentive analysis. The chapter highlights the diverse institutional landscape within the MDV, characterized by various governance modes. Within this context, aquifer systems are considered integral sub-SES within the broader MDV SES. The analysis suggests that while self-governance entities show promise in promoting rule adherence, state involvement is crucial, especially in monitoring and enforcement, depending on aquifer conditions, user attributes, and the clarity of resource system boundaries. In addition, while government-proposed aquifer contracts provide an institutional framework, significant adjustments are necessary to enhance resource user participation in decision-making processes and ensure robust rule compliance. These modifications are essential in fostering a collaborative and effective groundwater governance model necessary for ensuring sustainable management practices within the MDV.

Finally, **Chapter 6** reflects on the various chapters aiming to address the primary research questions outlined earlier. This chapter synthesizes the insights gathered from the various chapters and highlights the advantages and challenges inherent in the approaches employed throughout this dissertation. The chapter aims to draw conclusive remarks that not only inform future research directions but also provide policy recommendations.

Chapter 2

Analyzing stakeholder perceptions of water ecosystem services to enhance resilience in the Middle Drâa Valley, southern Morocco

Imane Mahjoubi [a], Lisa Bossenbroek [a, b], Elisabeth Berger [a] and Oliver Frör [a]

[a] iES Landau, Institute for Environmental Sciences, University of Koblenz-Landau, 76829 Landau, Germany.
[b] CRESC—Centre de Recherches et d'Études sur les Sociétés Contemporaines Rabat, Rabat 10020, Morocco.

Adapted from the manuscript published in 2022 in MDPI Sustainability, 14, 4765, https://doi.org/10.3390/su14084765

2.1. Abstract

Freshwater ecosystems deliver an extensive range of ecosystem services (ESs), which are the benefits people obtain from their interaction with nature. Increasing pressure on water resources threatens the sustainable supply of water-related ecosystem services, especially in arid regions, as is the case for the Drâa Valley located in southern Morocco. With the long-term objective of contributing to a sustainable supply of important ecosystem services in the Drâa Valley, this paper analyzes stakeholder perceptions of water-related ecosystem services (WESs). To assess the different perceptions of WES, 35 semi-structured interviews were conducted with the inhabitants of three oases in the middle Drâa Valley, as well as 12 other interviews with key government officials. Based on our interviews, we reflect on two of the policy-relevant generic principles proposed by the Stockholm Resilience Centre for enhancing the resilience of WESs. Our results reveal similarities in perceptions of WES among stakeholder groups regarding provisioning services but marked differences regarding regulating and cultural services. The analysis suggests that these differences stem from stakeholders' different roles and activities in the area. In addition, socio-demographic, biophysical, and spatial aspects also shape how WESs are perceived in the area. Learning about similarities in WES perceptions can help build common ground among stakeholders. The recognition of differences can also assist in the balancing of the different needs and interests of these groups. ESS perception assessment can contribute to strengthened stakeholder knowledge of the categories of ESs and provide a common ground for participating in ES-related decision-making, hence enhancing resilience in social-ecological systems.

2.2. Introduction

Freshwater ecosystems deliver an extensive range of ecosystem services (ESs) (Maltby et al., 2011; Burkhard et al., 2012). ESs can be defined as the benefits people obtain from their interaction with nature (Costanza et al., 2008; Ernstson et al., 2013; Reyers et al., 2013; Huntsinger and Oviedo, 2014). These services underpin human well-being, which is founded upon the basic requirements needed to lead a good life (e.g., water, food, spiritual inspiration) (MEA, 2005; Guerry et al., 2015). However, many anthropogenic activities degrade ecosystems, with negative consequences for their capacity to deliver ES (MEA, 2005; Daily, 1997; Lewis and Maslin, 2015). One major challenge of the 21st century is to ensure an adequate and reliable flow of essential services from freshwater ecosystems to meet the needs of human populations; this can be particularly difficult in arid regions where precipitation is low and often irregular.

Since ESs emerged from people's interaction with nature, several approaches have been developed to conceptualize and analyze ecosystems and social systems as closely linked social-ecological systems (SESs) or human-environment systems (HESs) (Quintas-Soriano et al., 2021). Biggs et al. (2012) propose seven generic principles for enhancing the resilience of ESs in SESs that either relate to the properties of the system to be managed or to the system of governance. This approach defines "ES resilience" as the capacity of SESs to reliably sustain a desired set of ESs (Biggs et al., 2012). The Stockholm Resilience Centre helped clarify the large and growing work on SES resilience by identifying key underlying principles for building ES resilience and real-world applications of these principles (Folke et al., 2016). These seven policy-generic principles are designed to inform the practical governance and management of SESs at local, regional, and global scales (Biggs et al., 2015). They include: (P1) maintain diversity and redundancy; (P2) manage connectivity; (P3) manage slow variables and feedbacks. Principles that relate to key properties of the governance system are: (P4) foster an understanding of SESs as complex adaptive systems; (P5) encourage learning and experimentation; (P6) broaden participation; (P7) promote polycentric governance systems (Folke et al., 2016; Jentoft et al., 2007).

The Drâa River basin in southern Morocco is among the world's ten most arid river basins (Revenga et al., 1998). It can be viewed as an SES that faces several challenges that jeopardize sustainable water-related ecosystem services (WESs) supply. The Middle Drâa Valley (MDV) is an important part of the basin, where approximately 225,000 inhabitants depend on rainfed and irrigation agriculture in oases for their livelihoods (Revenga et al., 1998; Karmaoui et al., 2014). Recent analyses suggest that this type of agriculture may not be feasible soon due to dropping groundwater levels and water salinization (Johannsen et al., 2016; Terrapon-Pfaff et al., 2021). These events have generated a growing need for sustainable water governance in the MDV. However, questions arise regarding which ESs are essential for what, to whom, and how they should be prioritized and sustained.

ESs are likely to be valued differently by different stakeholders: a management strategy based on a single set of stakeholder perceptions may be unacceptable to other stakeholders (Hein et al., 2006). Experience has shown that conflicts can occur when values arising from different stakeholder groups are not properly understood (Adams et al., 2003; McShane et al., 2011; Vira et al., 2012). To better comprehend the different existing values, attitudes, and meanings that underlie the demand and use of ESs, several scholars have assessed the ESs perceptions of the different stakeholders (Iniguez-Gallardo et al., 2018). According to Sagie et al. (2013), such methods promote an understanding of the importance that local populations place on ESs. Furthermore, insights into people's perceptions of ESs and management options inform discussions on how to proceed when faced with tradeoffs among ESs (Elwell et al., 2018). This discussion also relates to two of the generic social-ecological system governance principles proposed by Biggs et al. (2012): learning and experimentation (P5) and broadened participation (P6).

With the long-term objective of contributing to a sustainable supply of essential WESs in the Drâa social-ecological system, the present study aims to: (i) identify WESs and the associated perceptions among local inhabitants in three MDV oases, and the governmental actors involved in decisions on water resources in the area; (ii) understand the differences in WESs perceptions amongst the two stakeholder groups; (iii) identify trends surrounding WESs perceptions, which ESs matter the most and to whom, and how the contribution to social well-being occurs. Finally, (iv) we want to reflect on two of the policy-relevant generic principles for enhancing the resilience of ESs in social-ecological systems based on our empirical observations in the Drâa River basin.

The paper is structured as follows. Section 2.3 describes the main natural and social features of the study area and explains the methods used for data gathering, organization, and analysis. Section 2.4 presents the results of the ESs perception assessment and services identification among stakeholder groups. In Section 2.5, we discuss our main findings against the background of our main research objectives. Finally, Section 2.6 concludes by reflecting upon the role of ES perception assessment in contributing to a sustainable supply of important ESs in the Drâa Valley.

2.3. Material and Methods

2.3.1. Study Area

The Middle Drâa Valley (MDV) is a territory of 15,000 km2 located in south-eastern Morocco (Figure 2.1). A belt of six oases extends over 26,000 hectares (ha) along the MDV (Karmaoui et al., 2014). The oases vary in the size and number of their inhabitants. Ketaoua is the largest, with over 7000 ha of farmland, while M'hamid in the far south is the smallest oasis, covering around 2000 ha of farmland (Heidecke et al., 2010). The MDV falls into two provinces of the administrative region of Drâa Tafilalet: Zagora and Ouarzazate. Zagora is the principal city in the MDV, with 40,067 inhabitants (Sagie et al., 2013), whereas Ouarzazate is located in the Upper Drâa and has 71,067 inhabitants (Sagie et al., 2013).

Surface water resources in the MDV consist of the Drâa River which flows from El Mansour Eddahbi Dam, which was constructed in 1972, upstream of the valley close to the city of Ouarzazate (Karmaoui et al., 2015). The area is characterized by its hot and arid climate, with increasing aridity along a north–south-east direction. The average annual rainfall in the region is around 200 mm in the north and 30 mm in the south (Terrapon-Pfaff et al., 2021). Due to its aridity, population, infrastructure, and agriculture are concentrated along the river and its oases (Heidecke et al., 2010). The MDV is an irrigation-based area where agriculture is the main economic activity (HCP, 2015; Martin, 2006) on which local inhabitants strongly depend. As a result, 97% of the total exploitable water resources, including surface and groundwater, are used for agriculture (Martin, 2006). Therefore, the reservoir's key importance is to provide water for agricultural use in the area and to recharge the six oases' alluvial aquifers (Berger et al., 2021; Klose et al., 2010). Released water is directed to the southern oases first, where it is retained in small reservoirs. From there, it is directed through a traditional canal system (Saguia) onto the fields and allocated according to traditional water rights. In each oasis, water resources are also managed by Water Users' Associations (WUAs) and their federation in the oases, which the government created in the 1990s. WUAs resulted from international debate on the development of participatory irrigation management (PIM) and irrigation management transfer (IMT) in large-scale irrigation systems (Kadiri et al., 2009; Van Vuren et al., 2004). The objective of the WUAs is to promote farmers' participation in the development, operation, and maintenance of irrigation infrastructure and to promote dialogue with regional agriculture organizations (Van Vuren et al., 2004).

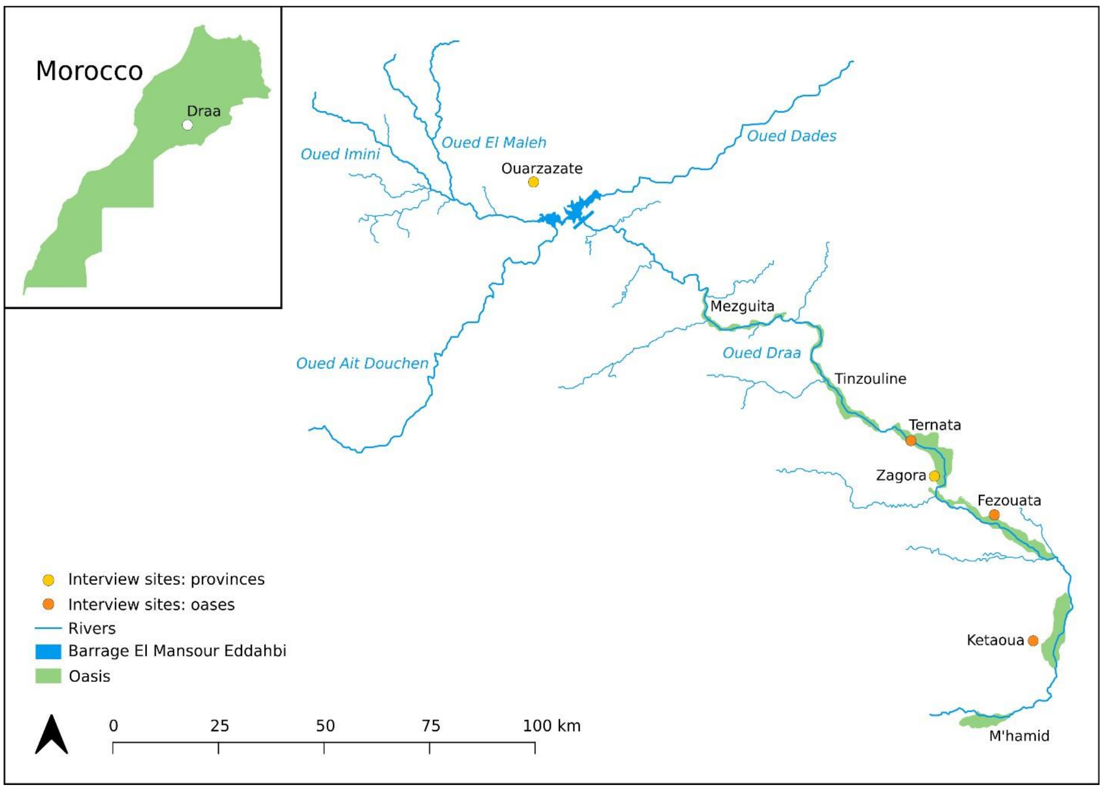

Figure 2.1. Location of the Middle Drâa Valley in Morocco; sampling locations of interviews with local inhabitants (orange dots) and governmental actors (yellow dots). (Terrain-basemape ©EOX)

2.3.2. Semi-Structured Interviews with Stakeholder Groups

To capture the diversity of the perceptions of WESs in the selected study area and to understand these differences in perception, we interviewed local inhabitants of the oases and governmental actors operating in the area.

2.3.2.1. Local Inhabitants

A total of 35 semi-structured interviews with local inhabitants (Table S 2.1; "S" for supplementary material) were conducted in March and June 2020 and during February 2021. These local inhabitants included 13 respondents from Ternata, nine from Fezouata, and 13 others from Ketaoua oasis. They were selected randomly through "snowballing" (the snowball sampling method consists of asking informants to identify other informants. (see Goodman (1961)) sampling (Figure 2.1). To determine the number of interviews, an indicator of saturation of the given information was used (Mason, 2010). After the 30th interview, no new perceptions were described. Therefore, 35 interviews were considered enough. The interviews focused on rural household water usage, personal views regarding water-related ESs, and the state in which the WESs are perceived and which factors shaped these perceptions, with potential follow-up questions for clarification purposes. The questions were adapted case-by-case to match the local context and level of understanding or to suit the terminology used in the area when necessary.

2.3.2.2. Governmental Actors

Twelve semi-structured interviews were conducted in February 2020 and February 2021 with ten key governmental actors in the water, agriculture, and tourism sectors in the MDV (Figure 2.1; Table S 2.1). The sample included interviewees from the Regional Office of Agriculture of Ouarzazate (Office Régional de Mise en Valeur Agricole (ORMVAO)); the Water Basin Agency Drâa-Oued-Noun (Agence du Basin Hydraulique (ABH)) based in Ouarzazate; the Provincial Delegation of Tourism (Délegation Provincial de Tourism (DPT)) situated in Ouarzazate; the Agricultural Subdivision in Zagora (Subdivision Agricole de Zagora—SAZ), which is a "field entity" related to ORMVAO; the National Agency for the Development of the Oasis and Argan Zones (Agence Nationale de Dévelopement des Zones Oasiennes et d'Arganier (ANDZOA)); the desalinization station situated in Zagora which was operating in the drinking water sector as part of the National Office of Water & Electricity (ONEE Zagora). The interviews focused on identifying the benefits derived by the human population of the oases from water resources, the key water management options and strategies implemented in the MDV, and the factors that drive these management options and strategies. The interviews were conducted with several actors who occupied different positions in each of the selected governmental institutions to clarify some statements (i.e., directors of institutions, engineers, technicians). Furthermore, documents shared by the actors, which were mentioned during the interviews, were considered to confirm some information.

The interviews were designed to last approximately 45 minutes for local water users and 60–70 minutes for government stakeholders. Each interview was recorded with the informant's consent. To gain a good understanding of the questions, unfamiliar terms such as "water ecosystem services" were avoided during the interviews. For example, the more colloquial term "benefits from water" was preferred.

2.3.3. Analysis of the Semi-structured Interviews

The interviews were transcribed and subject to content analysis using MAXQDA 2020 software (VERBI Software, 2020). We adopted the ES categories provided in CICES V4.1 by Haines-Young and Potschin-Young (2012) (Haines-Young, 2012) to assess the different WESs identified. The coding followed the steps suggested by Saldaña (2013). We combined a deductive approach (codes selected in advance based on our key concepts) with an inductive one (codes as they emerged from the interview texts). Codes established deductively are the main categories of ESs (e.g., provisioning, cultural, and regulating services). Specific words and sentences describing the use of water in certain activities or other benefits derived from water were highlighted to inductively generate subcodes and indicate the different services each of the categories contained (e.g., drinking, irrigation, crops, green spaces, smoothing the arid climate) for each of stakeholder group (Tables S 2.2 and S 2.3). To capture the diversity of the perceptions of WESs, we calculated the percentage of informants who identified each category of WESs (provisioning, regulating, and cultural services) from the overall services assessed (Haines-Young, 2012). For WESs prioritization, the percentage of respondents who ordered ESS as a first, second, and third priority for each group of stakeholders was calculated. We assessed the different WESs and analyzed text segments from the interviews with both groups to explore the extent to which the ES resilience principles (P5 & P6) had been covered. In particular, we closely looked for information that related to defining the resilience principles and that could support their possible application for the case of the Drâa Valley. Due to the limited sample sizes of the two stakeholder groups and the nature of the research questions, our analysis followed a qualitative approach to identify the trends surrounding ES perceptions and their determinants—this gave rise to new hypotheses.

2.4. Results

2.4.1. Water Ecosystem Services (WESs) Perceptions among Stakeholder Groups

2.4.1.1. Characteristics of Local Inhabitants Interviewed

Despite our random sampling of local inhabitants, more men (23 informants: 66%) than women (12 informants: 34%) were interviewed. This is explained by the low number of women who could be contacted through the snowball sampling method and because women were less willing to participate when asked to be interviewed. Those women interviewed at the level of the oases expressed hesitation and doubt when asked to describe their point of view about how water is supplied to the MDV. Most avoided answering, except for a few interviewees with whom the conversation was open and fluent.

Respondents were between 20 and 68 years old. They were farmers (59% of the respondents), workers (37% of respondents worked in the oases and cities as housemaids, construction workers, or in commerce), or of mixed occupation (4% practice farming together with other occupations). Among the interviewees were members of associations, such as the water users' associations (10%) and other types of agricultural associations and cooperatives (12%). Students comprised 2% of interviewees.

2.4.1.2. WES Identification per Categories of Ecosystem Services

During the interviews, we asked the stakeholders to state and describe the benefits derived from the use of water in the MDV. Eleven WESs, including five provisioning services, five cultural services, and one regulating service, were identified (Figure 2.2). Quotes and expressions from the local stakeholders that described the WESs identified are presented in Table S 2.4.

a. Provisioning services

Local inhabitants

Four types of provisioning services were identified by all interviewed local inhabitants (Figure 2.2). Interviewees identified drinking water as an essential source of life. In addition, they considered irrigation water to be vital for the survival of the oases, and crop production to be essential for the economy of the families which depended on farming. Informants explained that dates, wheat, barley, alfalfa, and vegetables such as gombos provide an essential source of food and income. Farmers identified dates as constituting one of the most important income-generating crops. Domestic water was also identified by all informants as being used for daily activities such as cooking, cleaning, and washing clothes and carpets.

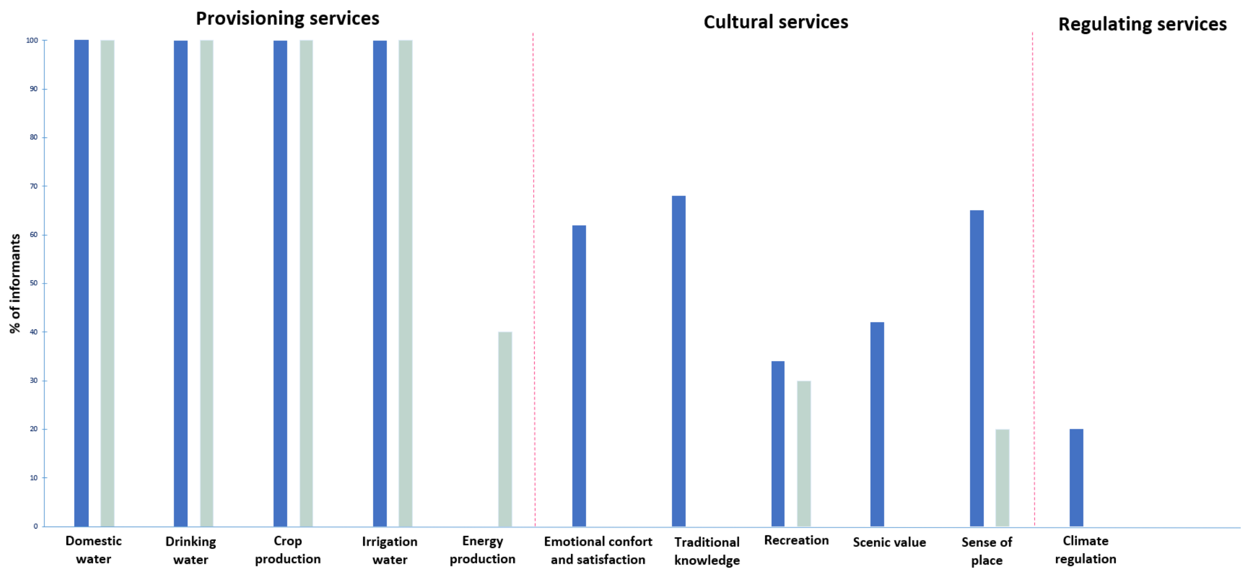

Figure 2.2. Percentage of local inhabitants (green bars) and governmental actors (yellow bars) identifying the various water ecosystem services (WESs).

Governmental actors

The same four provisioning services were also identified by all governmental stakeholders interviewed; in addition, six of these named energy productions as an ES (Figure 2.2). Specifically, they stated: “It is an area that begins with a large dam, whose purpose is primarily the supply of drinking water as well as irrigation water for the valley of Drâa”. All participants identified crop production as a direct output of water used for irrigation. Respondents from ORMVAO, SAZ, and ANDZOA identified date production as the principal and most valuable agricultural production in the area economically, given their high demand in local and national markets; furthermore, they added that such production also boosts the activity of several agrarian cooperatives and associations (e.g., economic interest groups—Groupement d’intérêt économique), as expressed by an interviewee: “Agriculture is among the main pillars and I can tell you that it is the engine of the economy of Drâa”. Energy production, however, was mentioned only by five participants from ABH, ANDZOA, ORMVAO, and SAZ (40%).

b. Cultural Services

Local inhabitants

Among local inhabitants, the survey results indicate that the presence of water inside the oases facilitates a broad range of cultural services. Of the overall cultural services assessed (Figure 2.2), 65% of informants perceived a sense of place and an identity from the water resources supplied to the oases. Most inhabitants referred to such a sense when referring to irrigation and crop production. They perceived water as preserving their local lifestyle as farmers and their identity as local inhabitants of the oases.

Palm trees especially represented the identity of the area for them. In addition, 68% of the informants claimed that knowledge of how water should be distributed among the local population, which represents traditional and customary rules, is acquired through water. Moreover, the interviews reveal that the different institutions that shape and organize the social dynamics around water also exist in the traditional use of this water. A farmer stated: “The Nouba (turn) system we use to distribute water has existed for almost 400 years now. We started learning about it when we were young. We were part of the water distribution process and helped maintain the canals at a very young age. We therefore understand well how the system functions and we still use it”. Some 62% of the respondents expressed feeling emotional comfort and satisfaction in receiving water and using it for irrigation. The scenic beauty was perceived by 42% of the informants, of whom 34% explained that water flow in the oases provides green spaces and vegetation; these, for the local population, provide opportunities for recreation such as picnics and river walks.

Governmental actors

According to five respondents from DPT, ORMVAO, and ANDZOA (30%), water resources provide recreational opportunities for local inhabitants and visitors from other areas. In addition, they stressed that the vegetation growing in the oases, such as palm trees, and almond trees, is a source of recreation. For these stakeholders, date production constitutes an essential component of the region’s recreation, tourism, and nationally significant beauty. Furthermore, palm trees and their fruit were considered by respondents from ANDZOA and ORMVAO (20%) as essential sources of identity for the area and its population; one informant expressed: “I say that the characteristic of the oasis is the date palm.” The same 20% claimed that water is critical for the existence of the oases and the provision of a sense of belonging for their inhabitants.

c. Regulating Services

Only one regulating service, climate regulation, was mentioned, and only by local inhabitants. Seven informants (20% of the local inhabitants sampled) mentioned that water flow—precisely, surface water—provides a favorable climate for living. The informants explained that climate regulation was provided by essential vegetation, such as palm trees, which promotes a cooling microclimate. Respondents referred to this service as “... providing a cool atmosphere ...”, “... refreshing the arid weather ...” and “The water helps to smooth the aridity of the weather a little bit”.

2.4.1.3. WESs Prioritization among Stakeholder Groups

When asked to put in order of priority the WESs, both stakeholder groups assigned the highest priorities to drinking water, irrigation water and crop production, and domestic use (Figures 2.2 and 2.3). However, the priorities assigned by local inhabitants were more heterogeneous than those of governmental actors.

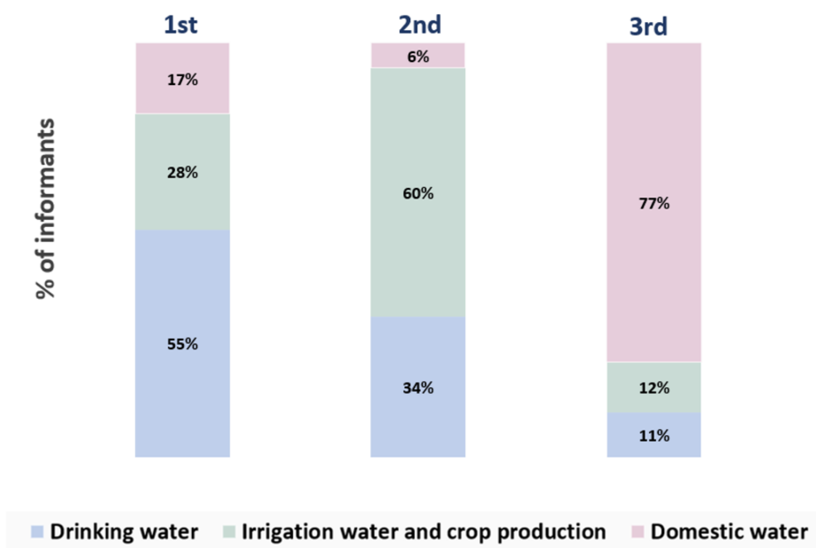

Figure 2.3. WESs ordered by local inhabitants (in percentage) as the first, second, and third priority.

In particular, while 17% of local inhabitants ranked domestic water as the priority, governmental actors consistently ranked domestic water as third. Moreover, while 11% of local inhabitants ordered drinking water as a third priority, 70% of governmental actors ranked it as first. Local inhabitants who ordered drinking water as the priority included men and women engaged in occupations unrelated to farming (e.g., construction workers, housemaids, commerce in the oases, and students). In addition, local inhabitants ranking irrigation water and crop production as second priority included mainly participants who practiced farming-related activities (e.g., farmers, cooperative members, WUA members, households practicing subsistence farming or consuming crops from local markets, and agricultural laborers).

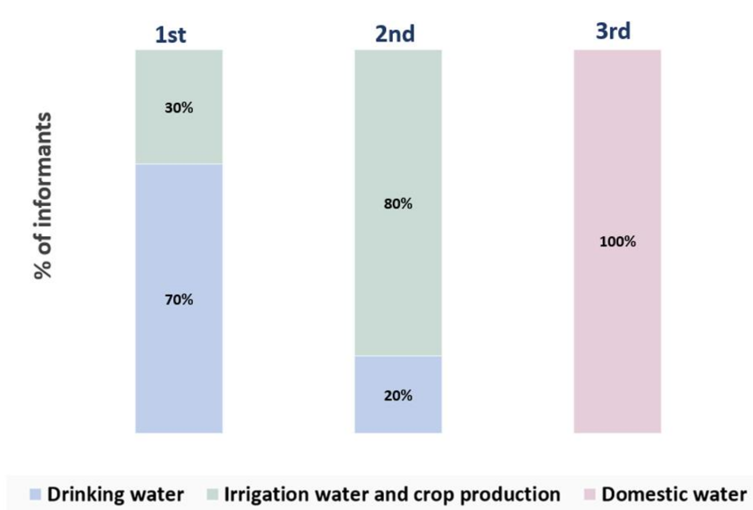

Figure 2.4. WESs ordered by governmental actors (in percentage) as the first, second, and third priority.

During the interviews, both stakeholder groups explained that they prioritized the services from the most to the least essential. Governmental actors stressed that they considered the most important criterion to be the existence of people in the Drâa; therefore, they focused on what was indispensable for the population and prioritized what contributed the most to the incomes of the majority of the inhabitants of the valley.

2.4.2. Factors Shaping Perceptions of WESs: Some Emerging Trends

2.4.2.1. Local Inhabitants

Place of Residence

Interviewees indicated that their place of residence—which varied geographically among the oases—might determine their perceptions of WESs. For instance, variables such as the proximity to the El Mansour Eddahbi Dam (Figure 2.1) and the distance from the river were volunteered as influencers of provisioning and cultural service perceptions in the oases. Residents in Ternata (28% of respondents), located upstream of Fezouata and Ketaoua, claimed to perceive more provisioning services than other oases. Due to its proximity to the dam, Ternata is among the first oases to benefit from water releases through aquifer recharge, in comparison to Fezouata and Ketaoua. Furthermore, respondents in Ternata and Ketaoua explained that living farther away from the Drâa River made it difficult for the water flowing in the canals to reach the villages located deep inside the oases.

Water Quality and Quantity

Interviewees from the three oases indicated that the water's perceived quantity and quality factored highly in determining perceptions of provisioning, culture, and regulating WESs. Respondents claimed that they tended to select water usage by looking at its quantity. Thus, the less volume of water they received, the fewer benefits were perceived. Non-farming respondents prioritized usage other than agriculture, such as drinking water for livestock or households. Furthermore, by looking at water quality (e.g., degree of saltiness, acidity, sweetness, pollution, etc.) we observed that farmers tended to select crops best suited to the quality of available water (surface or groundwater). For example, farmers in Fezouata and Ketaoua (62% of the respondents) preferred to use surface water released from the dam over the very salty groundwater to irrigate their crops (such as alfalfa, vegetables, and cereals). However, in Ternata, farmers (37% of the respondents) depended more on groundwater, as they perceived the river water to be polluted. All respondents who identified scenic beauty associated the beauty of the landscape, its vegetation, and air quality with the quantity of water flowing in the river. Respondents thought that farming in the oases could only continue with a sufficient quantity and quality of water.

2.4.2.2. Governmental Actors

Interviews with governmental stakeholders highlighted how management strategies and policies shape their perceptions of WESs. The main focus of all interviewees was the dam construction policy. Two respondents from the Water Basin Agency (ABH), which manages dams and other infrastructure in the Drâa region, claimed that meeting the water needs of the local populations, the survival of the region, and protection from floods were the essential drivers behind the construction of the MDV dams. When referring to the projects and activities of the different institutions, the majority of respondents tended to refer to the supply of water-provisioning services (e.g., agriculture, water for irrigation, etc.). In addition, most respondents stated that the different strategies and development policies implemented to manage water in the area promote agriculture as an important sector of the region's food and income security.

2.4.3. The Perceived State of WESs and Local Institutions in Providing WESs to Local Inhabitants

2.4.3.1. The Perceived State of WESs

Local inhabitants shared similar perceptions of the state of WESs. The majority claimed a negative perception of the irrigation water supplied to the MDV. Of this group, 66% identified declining water quantity as a prime concern for the future conditions of the MDV. Residents in Ketaoua (37% of the sample) identified increasing salinity levels and declining palm tree vegetation as key concerns. All of the oases' inhabitants interviewed claimed to perceive some essential crops as being of poor quality—for example, date fruits during the last five years. For 60% of the respondents, a sense of place and identity, and scenic beauty stood out as being perceived negatively compared to ten years ago; they were referring to the reduced water flow in the oases and existing and newly constructed water infrastructure along the Drâa River. In this sense, Ketaoua's residents referred to the presence of a deviation dam, built at the beginning of the oasis, from which they received water through cement canals; these prevented the natural river flow and the recharge of their aquifers. Similar results were found from farmers from Fezouata and Ketaoua concerning traditional knowledge in the oases. Participants from these two oases noticed a decrease in farming among the younger population and even a loss of skills linked to water scarcity (e.g., young individuals abandoning a field left by their parents). According to the same group, the number of people willing to occupy a position in traditional water management institutions within the oases has decreased. Moreover, due to less available water, older people tend to farm less, which reduces the transfer of knowledge. For Ketaoua's residents, this can also be explained by the fact that only a minority of young people are still interested in farming. The majority of respondents from Ternata, Fezouata, and Ketaoua perceived that the supply of drinking water was in a significantly better state than in previous years because it is now provided by a diversity of entities such as the National Office for Drinking Water (Office National de l'Eau Potable (ONEP)), communes, local associations and collective actions inside within oases. However, most respondents also perceived that many families in the MDV still struggled with drinking water availability.

2.4.3.2. The Role of Local Institutions in WESs Provision

The local inhabitants interviewed indicated the important role of several local institutions in surface water allocation, including the water user's associations (WUAs) and the jem'âa (the Arabic word for "meeting". It refers to an assembly, usually of elders and notables, or an "informal" socio-political framework, that allows members of a rural community, often a village or a group of villages, to meet and discuss issues related to the organization of collective assets, such as rangelands, the mosque and water hydraulic equipment (Rachik, 2001)). In particular, demands for material for irrigation canal maintenance or small water infrastructure construction are all made through the WUAs, according to farmers. Interviewees from Ketaoua also explained that individuals in managerial roles, particularly "the Ailam" (an individual responsible in the community for overseeing water distribution), are capable of adjusting the traditional system (the "clock system", also referred to as water turns, used to distribute water according to traditional water rights held by each water user). Such managers are responsible, depending on the amount of water available, for everyone receiving his/her share of the water released. Further, respondents who occupy presidency positions in the WUAs stated that they usually report water issues and concerns directly to governmental organizations (e.g., ORMVAO, ABH) or to other local institutions or authorities such as provinces, communes, or cercles (intermediate administrative units of the local authorities). However, respondents highlighted that some WUAs were non-functioning due to tensions between different ethnic groups who occupied key roles in the associations. Moreover, some respondents indicated the difficulty of approaching the right actors for specific water issues at the provincial and commune levels (e.g., well-digging permits and land-property issues).

2.5. Discussion

2.5.1. WES Perception Assessment among Stakeholder Groups

2.5.1.1. Identification of the WESs

This study revealed that stakeholder groups recognized both the direct and indirect WESs provided by the local ecosystems, as reported in other studies (O'Connor and Joffe, 2020; Campos et al., 2012; Fagerholm et al., 2012). All informants from both stakeholder groups perceived direct or provisioning services (e.g., crop production, irrigation, drinking, and domestic water) to a greater degree than indirect services, as reported previously (Campos et al., 2012; Fagerholm et al., 2012; Martín-López et al., 2012). In a subsistence economy based on the primary sector, particularly in developing countries, it is understandable that provisioning services are more valued than other services, as they are fundamental for the livelihood of local people (Fagerholm et al., 2012; Iftekhar and Takama, 2007). Therefore, as noted by Guerbois and Fritz (Guerbois and Fritz, 2017), provisioning services were also more frequently perceived and prioritized among local inhabitants of the MDV oases and governmental actors than other categories. One important difference between the groups, however, regards the energy produced by the dam: it was not mentioned once by local inhabitants. This may be due to a lack of local awareness of hydropower production and whether they are benefiting from it. This specific point requires further research. Furthermore, several studies have emphasized the perception of indirect services by rural residents (Campos et al., 2012; Martín-López et al., 2012). Similarly, in the present research, local inhabitants showed an appreciation of cultural services such as a sense of place, identity, and scenic beauty as benefits derived from water, probably because water resources play an important role in maintaining their lifestyle and preserving the oases' ecosystems. Given the droughts the area suffers from, cultural characteristics seem to come more to the fore. The lack of farming opportunities pushes people out of agriculture to pursue livelihoods elsewhere, with a consequent loss of identity. As Berger et al. (2021) concluded, access to water is essential to fulfilling one's identity as a farmer and local inhabitant. The fact that governmental actors referred less to cultural services can be explained by the scope of the different governmental agencies and the approach each of them adopts. Regarding regulating services, climate regulation was the only service mentioned—only by seven respondents, all local inhabitants, and associated with the water supplied to the MDV. This illustrates that, as found by Zhang et al. (2016), residents still have relatively low awareness of existing regulating services. Finally, as per Silvano et al. (2005), we also found that local inhabitants possess ecological knowledge of the importance of water for the environment and oasis ecosystem services, such as the maintenance of good air quality, the regulation of the microclimate of the oases through vegetation such as palm trees, and the reduction of aridity.

2.5.1.2. Factors Shaping Perceptions of WESs: Emergent Trends

This analysis highlighted that the current policies, responsibilities, and plans of governmental institutions contributed to shaping WESs perceptions among governmental actors. However, our study also revealed trends related to gender (see also (Hartter, 2010; Rockstrom et al., 2014; Barrera-Bassols et al., 2005), occupation, source of income, place of residence, and water quality and quantity surrounding ES perceptions amongst local inhabitants. In recent years, various studies have revealed that perceptions of ecosystems as sources of particular services can vary among respondents as a result of a complex set of factors (Fagerholm et al., 2012; Martín-López et al., 2012; Muhamad et al., 2014; Dolisca et al., 2007). Our analysis highlighted that men and women in the oases perceived and experienced cultural ecosystem services differently. Men derived a sense of identity, belonging, and emotional comfort from their farming activities, their lifestyle as farmers, and their interaction with water (e.g., irrigating the land, turning on the pumps, or clearing the canals). Female informants mainly linked cultural services to their domestic activities in the riverscape (e.g., cleaning clothes and carpets, harvesting activities, feeding the herd, and domestic work). Although these activities occur in the same environment (i.e., in the oases), the gendered labor division and the limited participation of women in formal farming and irrigation organizations may contribute to the fact that they have different perceptions. Our analysis further revealed that WESs perceptions also partly relate to respondents' occupations and sources of income. In particular, respondents who derived income from farming perceived more provisioning services: water for irrigation and crop diversity (e.g., dates, cereals, vegetables, etc.). Furthermore, individuals with local sources of income perceived more cultural services and experienced the beauty of the area in its different seasons compared to individuals working for long periods outside the oases. Place of residence appears to influence rural people's perceptions of ecosystem services. As reported in previous studies (Hein et al., 2006; Fagerholm et al., 2012), as well as contextually depending on the needs, choices, and values of the people, ESs are also related to place and tend to vary in geographical space within a landscape. Spatial differences within a landscape can lead to changes in the flows of ecosystem services and the reallocation of the benefits accrued from this landscape (Hein et al., 2006). Among the various spatial variables that might be related to the place of residence and which might influence the perceived ecosystem services in the MDV oases, we identified proximity to the El Mansour Eddahbi Dam: oasis inhabitants closer to the dam perceive more water. Fagerholm (Fagerholm et al., 2012) also noted that distance from respondents' homes to the landscape elements that provide ESs was an important indicator of the spatial pattern shaping people's perceptions of these services; this was represented in our study by distance from the Drâa River. Our results stress that access to water in terms of quantity and quality has a significant role in determining people's perceptions of WESs. Changes in the availability or quality of water and the above-mentioned spatial variables may affect their well-being, limit their benefits, and make agriculture and the enjoyment of the riverscape difficult. Therefore, decision-makers consideration of these variables is required for a better-informed surface water allocation in the MDV oases; this requires further research.

2.5.2. Contrasting WESs Perceptions: Which WES Matters the Most to Whom?

Our findings hint at similarities and differences in perceptions of WESs among local inhabitants and governmental actors (Figure 2.2). The similarities are mainly related to identifying and prioritizing similar provisioning services, whereas the differences are mainly related to energy production as well as regulating and cultural services identification. The differences point to the interaction of the stakeholders with the local ecosystem and the ecosystem knowledge they hold. This interaction may determine the ability of stakeholders to identify indirect ESs, as reported previously (Campos et al., 2012; Muhamad et al., 2014; Karmaoui et al., 2015). This difference also hints at the different roles each stakeholder plays in the area (local beneficiary or manager of the WES or institutional actors). For instance, local inhabitants identified the services most closely linked to their livelihoods, their subsistence and main source of income, and considered provisioning, cultural, and regulating services essential to their well-being. On the other hand, governmental actors mostly identified water provisioning services; this is in line with the actions and drivers of water management in the area. Furthermore, the differences in WESs perceptions between both stakeholder groups were reflected during the interviews, and the process of assessing these perceptions was different for local inhabitants and governmental actors. In particular, local stakeholders spontaneously attached different intangible values and senses to the ESs and narrowed the answers using descriptions of the ecosystem elements (Table S 2.4). In contrast, governmental actors described ESs and their purposes more formally and from the perspective of their specific sector. Perceptions of WESs can vary across stakeholder groups but they can also vary within each group. Different ES perceptions indicate an opportunity for stakeholder groups to interact in one system and to learn which ESs matter to other stakeholder groups and members of the same group. They can then adjust their management or consumption actions to maintain these services. At the same time, as we will discuss later, similarities in WESs perceptions can also contribute to a common ground of understanding amongst stakeholders to discuss the availability long-term and sustainability of WESs.

2.5.3. Relevance and Possible Application of the WESs Perception Assessment

In this final section, we reflect on two policy-related generic principles—learning (P5) and broader participation (P6)—for enhancing the resilience of ESs in social-ecological systems as proposed by Biggs et al. (2012). Based on our interviews conducted in the Drâa River basin, our objective is to show how ES perception assessment can be used to inform the learning process and promote the participation of stakeholders in real-world settings, as well as deriving recommendations for Drâa Valley water resource management. As far as we are aware, the contribution of ESS perception assessment to enhance their resilience has not been extensively analyzed before. Furthermore, compared to ES studies conducted in the Drâa River basin (e.g., Zerouali et al., 2019; Karmaoui et al., 2019; Lopez-Rodriguez et al., 2019), our study includes cultural services and emphasizes the importance of their consideration in decision making.

2.5.3.1. Learning (P5) amongst Stakeholder Groups

The assessment of ESS perceptions conducted in this study allows an understanding of how the different actors who interact in the MDV perceive and prioritize ESs similarly or differently. As Biggs et al. (2015) concluded in the resilience framework, actors' knowledge is always incomplete in the face of inevitable uncertainty, change, and surprises in complex social-ecological systems; thus, arises the need for learning. In our case, the learning process could enhance a common dialogue on ESs by bringing the different actors together to discuss the Drâa Valley's long-term development vision, which is to attain a sustainable supply of ESs as identified by the various stakeholders. Nevertheless, due to greater climatic variations and the increased use of water resources, not all WESs may be supplied in sufficient quantities in the near future. Which WESs to prioritize and what trade-offs might be required may become important themes. Here, as mentioned by López-Rodríguez et al. (2007), learning could enhance dialogue and understanding of the ESs approach to support transformative social change in governance practice. In the current example, the learning process is termed “sustainable” or “transdisciplinary” learning, being a tool for facilitating constructive dialogue between groups of actors (Schneider et al., 2009; Tengo et al., 2017)—local inhabitants and governmental actors in our case. For there to be true dialogue and mutual understanding, it is essential to make different kinds of knowledge accessible and understandable for the various participants (see also Barthel et al., 2010). Moreover, learning also needs to occur among the different groups of governmental actors and local inhabitants. Both groups have heterogeneous characteristics in terms of interests and priorities, which require better exchange and coordination to improve the local management of ES. We agree that the learning process is effective if it is collaborative (Cundill et al., 2009), which means that scientists, water decision-makers, civil society, and local water users must be involved. A long-term vision is also needed, which can withstand the impact of short-term politics and objectives (Armitage et al., 2009). Power dynamics can influence how learning occurs, who is learning, the relationships between learners, what type of learning takes place, and whose knowledge is integrated or discarded (Maarleveld and Dabgbégnon, 1990; Sousa et al., 2013). In our case, an example would be the powerful and influential role of the provincial authorities in the MDV, which can either help or hinder local knowledge exchange and learning. Furthermore, powerful governmental actors can strongly affect whose knowledge is considered or ignored, leading to the exclusion of some local individuals’ knowledge. Learning and dialogue could enhance the importance of administrators looking beyond sectorial boundaries; this is important for oasis regions considered to be agricultural areas but are also natural ecosystems that help prevent desertification and have rich biodiversity and local cultures. At this point, the learning principle is subject to questions. How feasible would be the application of a learning process in the MDV? How collaborative do the different stakeholders need to be for this process to happen? How much will powerful decision-makers be willing to learn and from whom among local communities? Finally, how can a learning space for this particular group of stakeholders be created, since the WESs of policymakers seem to be much influenced by larger water management plants?

2.5.3.2. Broader Participation (P6) of Stakeholders in the Management Process

Our results highlighted the existence of different local and traditional institutions (e.g., the WUA, the jem’âa, the Ailam). Interviews with members of traditional institutions revealed their experiential knowledge in managing water resources and other matters inside these communities. These results point to the importance and possibility of local communities actively participating in the management of water together with governmental actors, thus incorporating their knowledge into new management strategies. This may help safeguard existing traditional community knowledge about how water is managed. Moreover, when local communities identify with decisions, they might be more willing to accept them and maybe more compliant in their enforcement (see also Sousa et al., 2013). As such, the active engagement of local and traditional institutions in dialogue regarding water governance could contribute to the resilience of ESs in the Drâa River basin by including different views and perspectives (farmers, water users, association members, local leaders, etc.) in dealing with disturbances and changes in such a social-ecological system (e.g., droughts) (see also Pietrucha-Urbanik and Rak., 2020). It is, nevertheless, important to consider power inequalities in participation between stakeholders and among stakeholder groups. Additionally, a more honest assessment of the costs and benefits to individuals of becoming involved in such processes should also be considered (Cleaver, 1999). In considering the MDV case, the participating actors and their motivations for doing so are critical elements that require further research.

2.6. Conclusions

In this paper, we assessed and analyzed perceptions of WESs among different stakeholders and investigated how they may contribute to sustaining the future supply of these services in the MDV. In particular, we identified WESs and the associated perceptions among local inhabitants and governmental actors in the area, explored which WESs matter to whom the most and why, and discussed different factors that influence perceptions of WESs. One central result of our study is the existence of common ground concerning the identification and prioritization of WESs: both stakeholder groups prioritized the four most important WESs equally, resulting in provisioning services being considered the highest priority for people's livelihoods in the area. However, we also revealed a marked difference in WESs perceptions among both stakeholder groups regarding regulating and cultural WESs. We explain this difference by the various roles and responsibilities each stakeholder fulfills, their geographical location, and their current usage, access to, and the state of water resources. Against this background, we reflected on two of the policy-relevant generic principles for enhancing the resilience of ES in social-ecological systems: learning (P5) and participation (P6). Our assessment illustrates how the identification and associated perceptions of WESs amongst different stakeholder groups may open new pathways for joint learning and enhance dialogue for transformative social change in governance practices. For this to happen, we recommend broader participation, including by traditional and more recent institutions and diverse water users. During such a process, different future scenarios for the development of water resource management in the Drâa Valley could be discussed while envisioning what this means in terms of possible tradeoffs of the different WESs for the various stakeholder groups. Furthermore, information about the perceived state of ESs may also help practitioners and researchers to design management strategies that better address current shortcomings in ESs that are perceived as important yet considered by local inhabitants to be in a mediocre or poor state. In this sense, the ES framework could be useful in fulfilling the requirements of the resilience principles P5 and P6, in that it constitutes a common and comprehensive system for analyzing sets of benefits that different stakeholder groups perceive from water resources. In addition, it can foster communication about water resources and their various benefits between stakeholder groups for overcoming the inherent tendency of following largely sectoral approaches. Finally, our research points to the need for studies that can convey lessons learned in applying ESS approaches to actual decision-making processes that involve different interests, power relations, and politics at different scales of space and time (see also Kingdon, 1995). Such insights, gleaned from experience, would help improve the application of the ES framework to foster environmental decision-making processes that improve the resilience of ecosystems and people. Having achieved these insights, future research in the Drâa region will now focus on applying suitable environmental economic valuation approaches to generate transparent information on the benefits of the identified ecosystem services to be used by institutions and decision-makers related to water management in the area.

Chapter 3

Ecosystem services change from lost surface water for farming in the middle Drâa Valley, southern Morocco: An economic valuation through a replacement cost approach

Imane Mahjoubi [a] and Oliver Frör [a]

[a] RPTU - Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau - Institute for Environmental Sciences, Germany.

Adapted from the manuscript published in 2024 in Journal of Water and Climate Change.
https://doi.org/10.2166/wcc.2024.231

3.1. Highlights

- Applying the Replacement Cost Approach (RCA) in the Middle Draa Valley, Morocco, reveals both potentials and shortcomings in estimating ecosystem service losses due to reduced surface water.
- The costs for farmers to access groundwater as alternative vary across oases and are not aligned with the aridity gradient.
- Large farms gain from economies of scale in groundwater investments, demonstrating a greater willingness to replace lost surface water.
- Investment capacity, proximity to the dam, and income from crop production drive the willingness to replace lost surface water.
- Targeted incentives are essential to support small-scale farmers facing water scarcity.
- The analysis advocates for further studies to refine ecosystem services loss value estimations.

3.2. Abstract

Water scarcity in the Middle Drâa valley (MDV) in Morocco threatens self-sufficient farming, impacts agricultural production and livelihoods of the oases' population. To compensate for the lost surface water resources farmers increasingly access groundwater resources by digging and constructing wells for irrigation. In this paper, we test the replacement cost approach (RCA) to estimate the monetary value of irrigation water and the minimum amount of ecosystem services' value lost in the past. A cost-based survey of 107 randomly selected farms was conducted in 2022 to assess the costs of technical substitutes farmers used to replace reduced surface water over the past 20 years. We calculate replacement costs at farm and at oasis level and estimate their determining factors using multiple regression. The survey revealed that farmers' investment to replace surface with groundwater was positively correlated with farm size and the mean annual benefit from date production. Results show that the losses incurred from the loss of surface water did not follow the aridity gradient, and these losses varied due to water regulation practices, investment capacity, other income-generating activities, and other factors. Results suggest that the replacement is cheap per unit of meters dug, hectares and kg of dates, providing an advantage in terms of

economy of scale for large farms. The positive and significant regression coefficients suggest that large farms are willing to invest more, on average, to replace surface irrigation water used for irrigation. The analysis provides insights into the challenges faced by farmers, mainly small-scale ones, in accessing water resources and can contribute to forecasting farmers' behaviour and reasoning under water scarcity, which can be valuable for policymakers and development practitioners in the area. This analysis also contributes to the literature on ecosystem services valuation by providing a practical example of how the RCA method can estimate the value of different lost ecosystem services, and the challenges and opportunities it exhibited, which can inform future research on ecosystem services valuation and its implications for sustainable development.

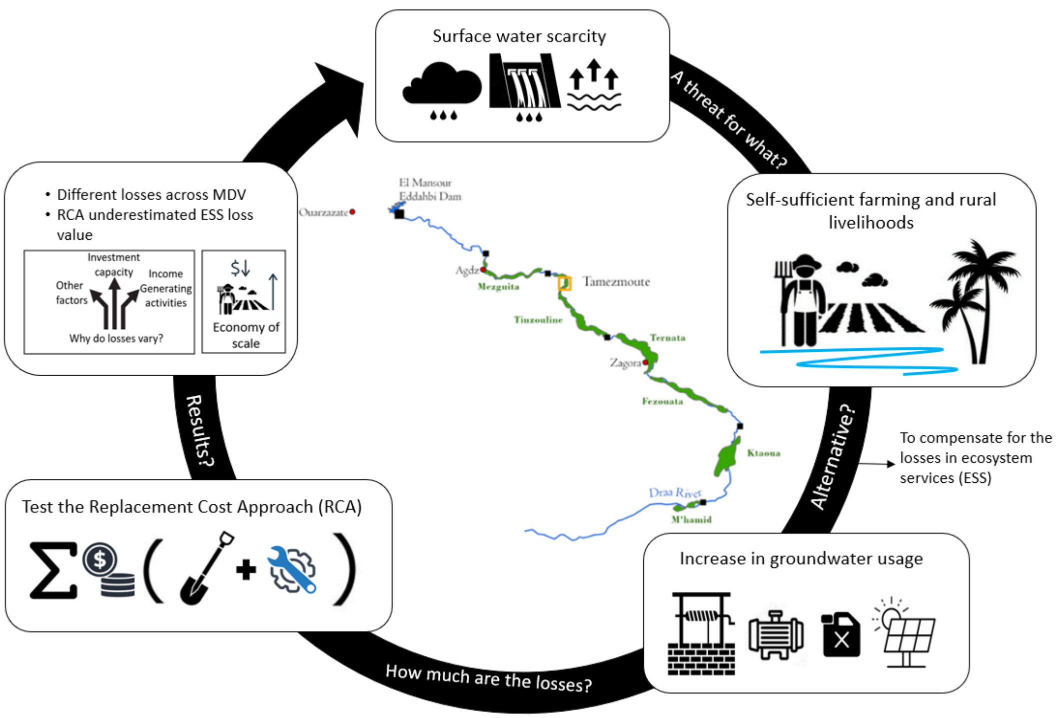

Figure 3.1. Graphical Abstract for Chapter 3.

3.3. Introduction

Regions with scarce freshwater resources, such as the Middle East and North Africa, face great challenges already today that will increase even more in the future due to climate change and population growth (Johannsen *et al*. 2016). Agriculture is the mainstay of the national economies of Northern African countries and the majority of the poor population works and lives in rural areas being highly dependent on water availability for sustaining their livelihoods (Kevin 2014). Available surface freshwater resources needed to meet this rising demand are increasingly endangered by human pressures, including climate change, land degradation, over-extraction of water, water pollution, deforestation, and urbanization (López-Morales and Mesa-Jurado 2017). Therefore, food provision and water security will rely not only on the remaining surface water, but also increasingly on groundwater, as aquifers constitute the largest available storage of freshwater (Diekkrüger *et al*. 2013) in the area.

Morocco's MDV faces water scarcity, salinity, and environmental challenges hindering economic development (Johannsen *et al*. 2016; Karmaoui *et al*. 2014; Moumane *et al*. 2021; Silva-Novoa Sánchez *et al*. 2022; Moumane *et al.* 2022; Kaczmarek *et al.* 2023). In particular, the MDV oases face severe water supply and management issues. Following the construction of Mansour Eddahbi dam in 1972, water was released periodically with each oasis receiving an allocated amount of water. Initially, 4-8 releases were planned annually (Johannsen *et al*. 2016; Karmaoui *et al.* 2019). Today, however, the number of releases has diminished to two annually, the average annual rainfall of 56 mm is observed in Zagora (Schulz 2006; Fico 2022) and 96 mm in Ouarzazate. The drought events are more frequent, where two droughts were of four years and one of three consecutive years have taken place in 20 years since 1980s (Ait El Mokhtar *et al*. 2019; Klose *et al*. 2008; Karmaoui *et al.* 2014; Terrapn-Pfaff *et al*. 2021). The oases are heavily impacted by water scarcity, with reduced water distribution and rainfall, and frequent drought events. This has severely affected agricultural production and livelihoods, resulting in a loss of ecosystem services most particularly the provisioning service of water availability, but also of further services like regulating and cultural ecosystem services (Karmaoui *et al.* 2016; Mahjoubi *et al*. 2022). To compensate for the lost surface water resources (i.e. Saguia water/dam releases), farmers increasingly tried to access groundwater resources by digging and constructing wells with diesel-fired pumps for irrigation with varying strategies and outcomes. By lost surface water we refer to water lost for farmers in the sense they do not find it available in the saguia when they needed it to irrigate their fields. In other words, we do not mean that water has disappear completely in the saguia, but we refer to a problem of timing and the increased uncertainty about the availability of this water. As a response to the loss in surface water for irrigation farmers may dig several shallow wells in different locations where they have partially functioning of non-functioning saguias (Jeddi *et al.* 2021). They may also choose to dig one deeper well in a specific location for more efficiency and lower costs if enough water is found.

The Moroccan government is developing policies for a preservation of water-related ecosystem services to counteract the threat of water scarcity in the region. Prioritizing water allocation among competing actors poses a significant challenge (Silva-Novoa Sanchez *et al.* 2022*)*. In order to make well-informed decisions, it is essential for regulators to comprehend the extent of loss in water-related ecosystem services among the traditional population of the Drâa valley in recent decades, to be in a position to consider the values lost in the decision-making process. The present study aims at contributing to provide such information. We use a replacement cost approach (RCA) (Sundberg 2004a; Wyatt 2009; Kang *et al*. 2015; Horváthová *et al*. 2021) to assess the costs of technical substitutes farmers put in place to improve or replace the surface agricultural water sources, subject to significant variability, over a period of 20 years. The timeframe was chosen following an initial exploratory interview phase, which also served to verify the method's applicability prior to conducting the survey and assess the farmers' perceptions of water-related events. This approach acknowledges that while water may be partially lost, efforts are made to improve or replace it through the adoption of alternative measures. The costs voluntarily spent by farmers to replace partially or fully this surface water are then interpreted as the minimum amount of ecosystem services value lost in the past. A survey with randomly selected farms in the MDV was conducted to calculate these replacement costs and understand local factors causing the replacement to take place.

In the present paper, we hypothesize that (1) the losses experienced by farmers are different for the various oases, specifically increasing from the northern oases to the southern ones and, therefore, the investments to compensate for the losses follow the same pattern. Studies show that in Ouarzazate city (North of the Drâa basin, Fig 1) the temperatures are lower and the precipitations are high compared to Zagora city in the south where temperatures are high and precipitation is low (Karmaoui 2019). In addition, from upstream to downstream, there is a remarkable decrease in the cultivated area of each oasis (Karmaoui *et al*. 2014). We further hypothesize that (2) for large farms with more production, more hectares, or deep wells, the replacement is relatively cheaper (per unit of production, per hectare, or per meter dug) and, therefore, the relative loss value per farm area is lower compared to small farms. We finally hypothesize that (3) farmers will invest larger amounts overall if they perceive greater annual benefits from growing dates.

The next section outlines the study area description, followed by the presentation of the general background and application of the RCA method. Then, section 5 and 6 show our results and a discussion of them, highlighting main concluding remarks in section 7.

4.1. Methods

4.1.1. Study area

The MDV in southern Morocco is a hot and arid region covering about 15 000 km² (Figure 3.2; Klose 2009; Martin-Igul 2006; Ouhajou 1996). Water for irrigation in the MDV is mainly supplied by the Mansour Eddahbi Dam, with an estimated annual demand of 250 million m³ (Klose 2009). Together with evaporation losses from the reservoir of at least 50 million m³/year, the total water demand for sustainable agricultural use of the MDV sums up to 300 million m³/year (Busche 2013). The Eddahbi dam's capacity has been reduced by approximately 25% due to high erosion rates and siltation (Diekkrüger *et al*. 2013; Klose 2009).

About 280,000 people live in the Middle Drâa catchment (Population count of 2014), distributed over the six oases (Platt 2008). Most oasis inhabitants are self-sufficient farmers who earn little income (Johannsen *et al*. 2016). They sell cash crops such as Alfalfa, Henna, and dates at local markets to buy fertilizers and fuel for groundwater pumps (Heidecke and Schmidt 2008). Household water consumption is much lower compared to agriculture (Heidecke and Schmidt 2008).

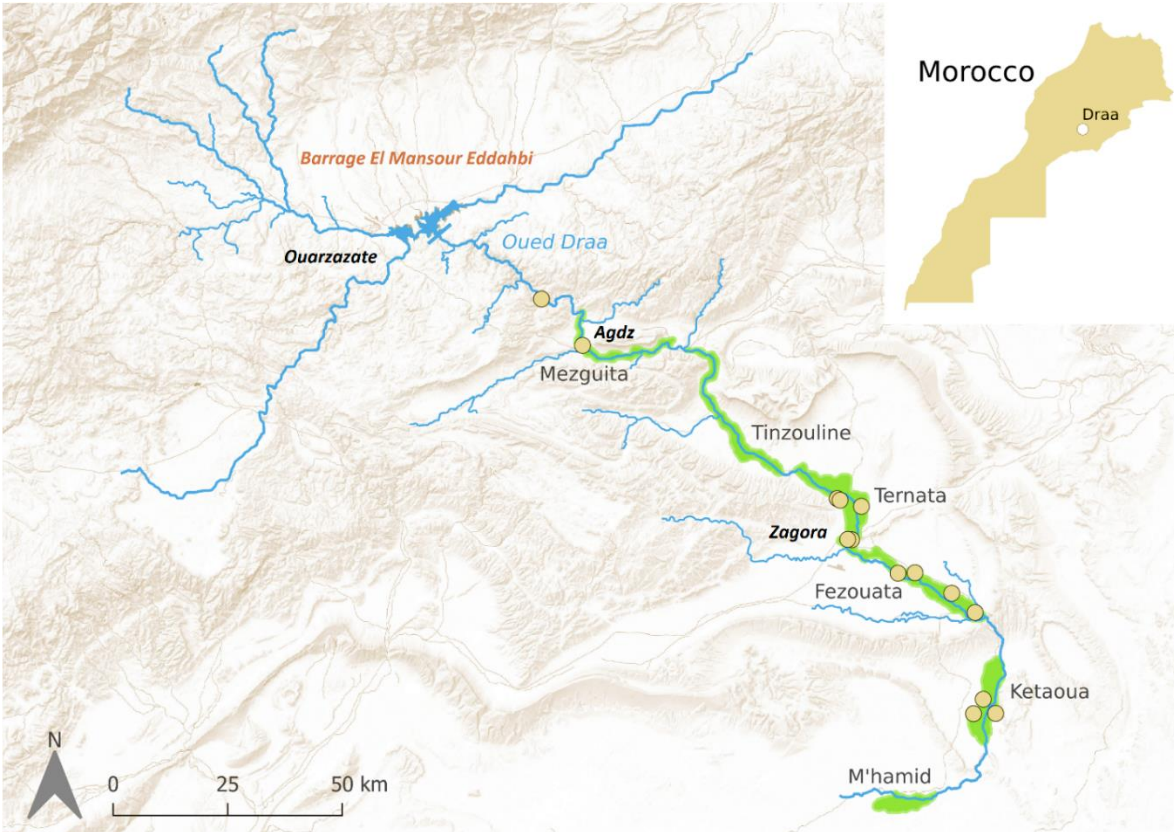

Figure 3.2. Map showing the Middle Drâa valley with its six oases (green areas) and the survey sites in 14 villages (points) (Terrain-basemape ©EOX).

4.1.2. The replacement cost approach (RCA): General background

The replacement cost approach (RCA) estimates the value of an ecosystem service by using actual market prices of a man-made substitute that provides a similar service (Chee, 2004; Wyatt, 2009; Kang et al., 2015; Horváthová et al., 2021). This approach considers both investment and maintenance costs to determine the replacement cost. The market and environmental goods can be either complements or substitutes (Sundberg 2004b). The cost of replacing an ecosystem service with a man-made substitute is used to measure the economic value of the ecosystem service.

The method is based on the possibility of finding (ideally) perfect substitutes to ecosystem services. For this method to be valid, three conditions must be met (Shabman and Batie 1978). See also Bockstael *et al*. 2000; Leschine *et al*. 1997; and Shiferaw *et al*. 2005. The first condition necessitates comparable substitutes in magnitude and quality, such as surface water provision. While finding perfect substitutes is rare, viable alternatives can often be utilized. The second condition involves employing cost-effective alternatives, prioritizing the least expensive man-made substitute to estimate the value of an ecosystem service. To obtain reliable cost estimates, it's practical to focus on a few available replacement techniques and study them in detail. The third condition is that urgent needs exist, and people are willing to pay for alternatives in the absence of the environmental good or service in question. Ensuring that people are genuinely willing to pay for alternatives prevents overestimation of the value of ecosystem services. For example, evaluating drinking water by looking at the costs of water provision by inter-basin transfer as an alternative, for which not all the community is willing to pay for or feel the real need of, would be an overstatement of the true value of the service. However, in our case, this condition cannot be violated since we look at alternatives (i.e. for irrigation water) already put in place and for which people were willing to pay for.

4.1.3. The RCA applied to the case of the Middle Drâa Valley

In this analysis, we intend to estimate farmers' losses in the MDV due to reduced surface water for irrigation over the past 20 years. To this end, we assess the costs of alternative irrigation water sources such as wells and tube wells. Our survey includes detailed information on drilling, construction, pumping with gas, fuel, electricity, or solar energy, and maintenance expenses. Specifically, we focus on the costs of constructing wells as substitutes for reduced Saguia water from dam releases, the traditional irrigation method of that region. The costs of deepening existing and newly constructed wells are considered as part of maintenance expenses. Additionally, we gather data on crop production, prices, and investments made by farmers to replace the lost ecosystem service of surface water provision at the oasis and farm levels. This comprehensive data is obtained through a detailed cost-based survey of farm households.

4.1.3.1. The average oasis replacement cost (across the entire oasis)

A “total replacement cost” (TRC) is estimated for each farm within each oasis by summing the primary and secondary digging costs. For each of the five oases, an “average oasis replacement cost” (AORC) per farm is estimated. It is measured in absolute terms from which relative costs per farm size in hectares, per meter dug, or unit of dates produced can be derived. The AORC in the present analysis refers to average values of farmers’ replacement costs estimated across the entire oasis. It is calculated as follows:

Equation 3.1. Average Oasis Replacement Cost (AORC)

$$\boldsymbol{AORC = \frac{\mathrm{TRC}}{N} = \frac{\sum_{n=1}^{N}(dc_n + sc_n)}{N}}$$

Where “***dc”*** refers to the primary digging costs of the farm, “**sc**” refers to all the secondary costs attached to the well digging activity, and “**N**” refers to the number of farms.

The average oasis replacement cost per hectare, meter dug, and kilograms of dates produced across each oasis are then calculated by dividing the AORC by the total hectares, meters dug, and date kilograms in each oasis in the period 2000-2021.

4.1.3.2. The mean digging cost at the farm level

To compare farms' digging efforts and related costs across oases and examine their investments in detail, we use the cost data collected for each farm to determine the "*mean digging cost per digging event at farm level*" (MDC), which represents the average amount invested per farm per digging event. Since digging efforts can vary due to different depths, we average the digging costs across events K of each farm. The term “mean” is used to differentiate the values measured in the context of farm-level activities from the average ARC measured across each entire oasis (see previous section). The mean replacement cost equation is as follows:

Equation 3.2. Mean Digging Cost at the farm level (MDC)

$$\boldsymbol{MDC = \frac{\sum_{k=1}^{K}(dc_k + sc_k)}{K}}$$

Similar to before, "***dc"*** refers to the primary digging costs, "**sc**" refers to all the secondary costs attached to the well digging activity, and ***"K***" refers to the number of digging events that took place in each farm.

The term "mean" is also used in this analysis to refer to values in the data set (e.g. mean meters dug per farm, mean annual quantities of dates produced, mean annual benefit of dates …). The mean replacement cost per hectare and meter is calculated by dividing the *MRC* by the number of hectares and total meters dug in each farm. The total RC per farm represents the sum of all primary digging costs and all secondary costs.

a. Determination of the MRC per units of dates

During the survey, each farmer reported two mean annual benefits (in Moroccan Dirham, MAD) obtained from producing and selling dates, their main crop, and their source of income. One benefit was before changes in water availability, and the second after. Two mean annual quantities of dates (in kg) produced before and after were also reported. The difference between the two benefits is the "mean annual benefit lost" (in MAD) and the difference in mean quantities produced is the "mean annual quantities of dates lost" during the period 2000-2021. To show the relative loss perceived by farmers, the replacement cost per unit of dates can be calculated. This allows a comparison of how hard farms were hit by the reduced water availability.

4.1.4. Survey design

In our cost-based survey, respondents reported expenses for seeking alternative sources of surface agricultural water within the Saguia system which is partially or no longer supplying dam release water. Our questionnaire had three parts: 1) Personal farming experience with changing water availability over the last 20 years, 2) Farming general details (size, products, quantities, income) and costs associated with current water sources using both closed-ended and open-ended questions, and 3) date changes fruit production (see Appendix 3.1). We asked about historical events and carefully examined the types of costs that needed to be assessed. We also requested written proof of costs whenever possible.

First, we conducted 38 in-depth interviews in MDV oases in April 2022 to gather an initial understanding of the lost ecosystem services or the ones at risk of being lost. Interviews were recorded, transcribed, and coded using MAXQDA 2022 software (VERBI Software 2021). The timeline feature of the software was used to document drought periods and their characteristics, and the ecosystem services categories proposed in the Millennium Ecosystem Assessment (Reid *et al*. 2005) were adopted for coding. Findings of the exploratory phase were used to develop a cost-based questionnaire, which was tested and used in September 2022 in a main survey of 107 households across 14 randomly selected villages across Agdz oasis (according to the locals) which is part of Mezguita oasis, Ternata, Zagora which is located before Fezouata but considered to be a separated small oasis according to the locals, Fezouata, and Ketaoua oases. We use the names Agdz, Ternata, Zagora, Fezouata, and Ketaoua to refer to our sampling sites, referring to them as oases. The questionnaire assessed economic, social, and farming information.

4.1.5. Multiple linear regression modeling

Multiple regression analysis was applied as a means for evaluating variables of the system using the R software. For hypothesis (1), a multiple linear regression model (A) (equation 3.3) was constructed to see whether the different TRC across the oases is a result of a farm size effect, or an oasis effect (reflecting the different aridities of the oases, increasing from north to south), or a combination of both. To analyze this, we introduced binary-coded dummy variables for each oasis, using Agdz as the reference category against which the other four oases were compared. The model can be written as follows:

Equation 3.3. Multiple Linear Regression Model A

(A) **TRC** = α + β1* Farm size + β2*Oasis Fezouata + β3*Oasis Ketaoua + β4*Oasis Ternata + β5*Oasis Zagora + β6*(Farmsize*Oasis Fezouata) + β7*(Farmsize*Oasis Ketaoua) + β8*(Farmsize*Oasis Ternata) + β9*(Farmsize*Oasis Zagora) + ε

where TRC is the dependent variable of the model, α represents the expected intercept of the model, β1, β2, β3, β4 and β5 are the coefficients of regression indicating the strength of the effect of farm size and features of each of the oasis as independent variables on the dependent variable, and β6, β7, β8, and β9 are the coefficient of regression for the interaction terms between farm size and each of the five Oasis, representing the significance of the effect of both independent variables combined.

In addition, three multiple linear regression models B1, B2, and B3 (equations 3.4) were constructed to examine the validity of hypothesis (2), and to explore what the relative costs per hectare, meter of well dug and Kg of dates produced depend on. *γ* represents the intercept in the three models and A1, A2, A3, A4, and A5 are the coefficients of regression indicating the strength of the independent variables. To test all the relative variables, we write the models as follows:

Equations 3.4. Multiple Linear Regression Models B1, B2 and B3

(B1) **TRC/hectare =** γ + A1. farm size + A2. Mean meters dug + A3. Total meters dug + A4. Mean annual date benefit + ε

(B2) **MDC/meter dug** = γ + A1. farm size + A2. Total meters dug + A3. Mean annual date benefit + ε

(B3) **MDC/Kg of dates =** γ + A1. farm size + A2. Mean meters dug + A3. Mean annual date production + A4. (Farm size *Mean meters dug) + A5. (Mean meters dug * Mean annual date production) + ε

Finally, a fourth linear regression model C (equation 3.5) was constructed to examine hypothesis 3 and to verify if the replacement costs of a farm depend on its annual date benefit or not. For this, we use the TRC as a dependent variable. X is the intercept and the Y1 is regression coefficient for the independent variable. It is represented as follows:

Equation 3.5. Multiple Linear Regression Model C

(C) **TRC** = x + Y1. farm size + Y2. Mean annual date production + Y3. Mean annual date benefit + ε

4.1.6. Adjustment of monetary figures

Since the monetary information assessed in the survey is over the period from 2000 to 2021, all figures need to be referenced to the same year. We chose 2021 as the reference year and consequently inflated all monetary figures using the average inflation rate for consumer prices in Morocco for that period of 1,48% annually. In addition, the two mean annual benefits from producing dates from before and after the changes in water availability were inflated using the average inflation rates of both periods (i.e. for 2000-2021, the average inflation rate was 1.48%, and for 2012-2021, the average inflation rate was 1.18%) (Table S 3.1).

4.2. Results

In this chapter, we first present the basic characteristics of the surveyed farmers to provide a context for understanding the local agricultural practices and farming systems in the area. Next, we present an overview of people's perceptions of drought events and ecosystem services since the 80s. Finally, using our cost data, we provide an estimation of the replacement costs of lost surface water first across each oasis, and secondly at the level of each farm, where we try to compare the investments between oases, and within each of the oases' farms. In both parts, we use multiple regression modeling to test our hypotheses (see section 3.1).

4.2.1. Characteristics of the surveyed farmers

From 107 farmers interviewed, we found that 78% use replacement sources (wells and tube wells), partially in combination with available dam releases, while the remaining 22% fully use wells. Funding for well-digging comes from farming income (for 44% of farms), remittances only (19%), or both (33%). Among the farms, we identified 129 wells dug in 212 events, totaling 3879.5 meters (average well depth is 30.07 meters). The farms grow various crops, with over half of them focusing on dates, 11% mixing dates and fruits, and some mixing dates with wheat, vegetables, and alfalfa.

4.2.2. Overview of people's perceptions of drought events and ecosystem services since 1980

In our exploratory interviews, we inquired with local individuals about their perceptions of the oasis ecosystem in previous years. The majority of respondents cited specific events and periods, including the construction of the El Mansour Eddahbi dam in 1972, and various drought periods. We specifically requested information on the droughts of 1982 and 2012, as well as the current ongoing droughts, and asked interviewees to identify unique characteristics of each period.

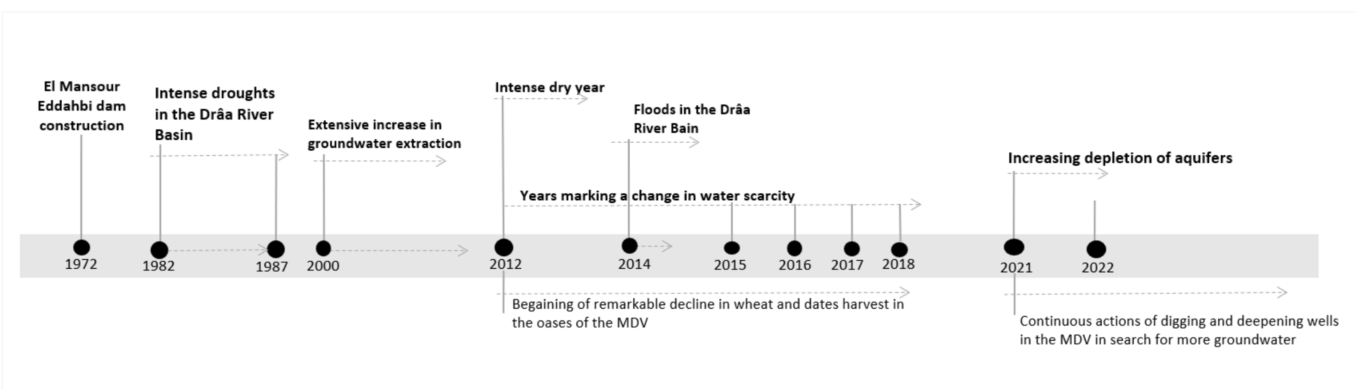

Figure 3.3. Water-related events identified by the interviewees.

Interviewees over the age of 45 from Mezguita, Ternata, Fezouata, and Ketaoua expressed that the Drâa Valley was thriving and healthy during the previous period of independence. The ecosystem provided many essential services, such as drinking water, river flow, and scenic beauty, as well as many other cultural services. However, severe droughts from 1982 to 1987 drastically reduced surface water availability, affecting the oasis ecosystem and livelihoods. The interviews noted that aquifers remained charged during the 1982 droughts likely due to the relatively low use of aquifers and water pumps before 1982 and sufficient dam releases. However, some regions still experienced heavy losses in surface vegetation. Respondents revealed that many palm trees were preserved due to the wet and moisturized aquifers. Nevertheless, participants claimed that several regions in the Drâa basin experienced heavy losses in surface vegetation, including almond, olive, and palm trees.

According to the interviewees, between 1982 and 1987, wells in oases increased, mostly manually dug and less than 8 m deep, mainly in Fezouata and Ketaoua. Since 1990, fuel and gas water pumps have been used. A decade after the droughts, aquifers had increased in salinity, especially in Fezouata and Ketaoua. According to the interviewees, there was an extensive use of groundwater, increasing from 2000, and leading to severe impacts from the 2012 droughts on the oases and their ecosystem services. The droughts lasted two years and were followed by floods in 2014. Current droughts have been ongoing since 2015, according to some interviewees, and since 2016 according to others, while only a few mentioned 2017. Interviewees reported the loss of farming-related ecosystem services from the 1982 droughts to the current droughts, with only a few of these services being replaced. Insufficient water for farming is a major concern for most of the interviewees, and while most were able to replace a portion of the lost surface water, there has been an irreplaceable loss of cultural services.

4.2.3. Estimation of the average oasis replacement cost (AORC)

Based on the TRC formula and differentiating for the oases, Agdz oasis, in the north of the MDV, has the highest TRC range for replacing lost surface water at an average investment of 8093 MAD, while Zagora marks the lowest range with 5906 MAD (Fig. 3). Investments do not follow a clear pattern from north to south but they decrease from Agdz to Zagora, increase in Fezouata and then decrease in Ketaoua.

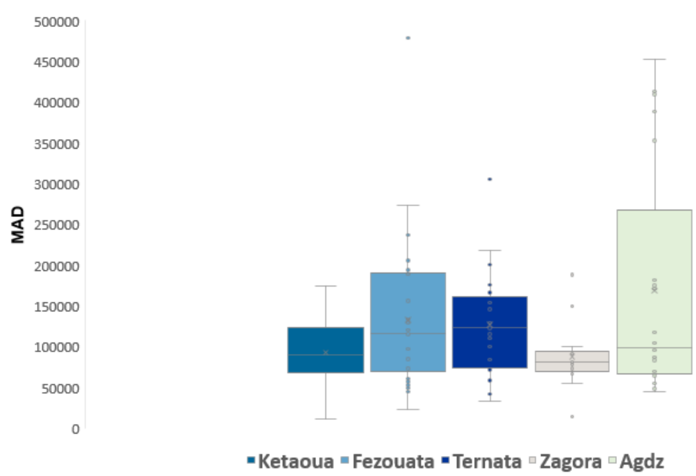

Figure 3.4. Distribution of the TRC (in MAD) across oases. The box represents the middle 50% of the data or the interquartile range. The line in the middle of the boxes represents the median, whereas the X represents the mean. The bottom edge of each box is the first quartile (25%), and the top edge of the box is the third quartile (75%). The whiskers show the range of the data beyond the box, but smaller than 100%, and the outliers or individual points outside of the whiskers indicate the full data range (100 %).

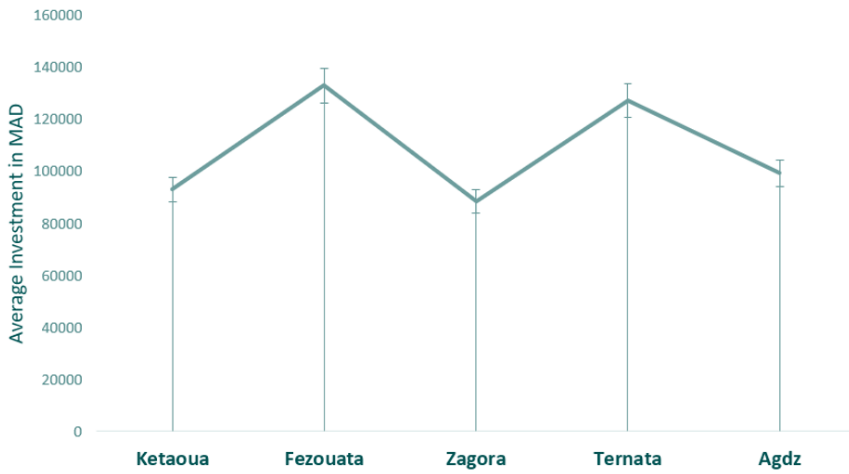

Figure 3.5. Average Oasis Replacement Cost (AORC) for each oasis.

Figure 3.5 illustrates the variation in average oasis replacement cost from the south to the north of the Drâa Valley. Agdz has the highest AORC, whereas the lowest was marked in Ketaoua.

4.2.3.1. Average oasis replacement cost (AORC) per hectare, meter dug, and kg of dates across an oasis

We examined the AORC per hectare of farm, as well as per meter dug across each entire oasis. Figure 3.6 shows that Fezouata has the highest average oasis replacement cost (AORC) per meter of well dug, per hectare of farm, and kilogram of annual date production compared to other oases. Comparing the total meters dug and the farm hectares per oasis (Table 3.1) with the AORC reveals no clear pattern of variation across the Drâa Valley. However, it is notable that oases with the highest numbers of hectares or meters dug tend to have the lowest AORC, as seen with Ternata in graph (A) and Fezouata in graph (B) (Figure 3.6). For lack of exact total quantities of dates, we couldn’t observe such a pattern for the kg of dates and AORC for the oases.

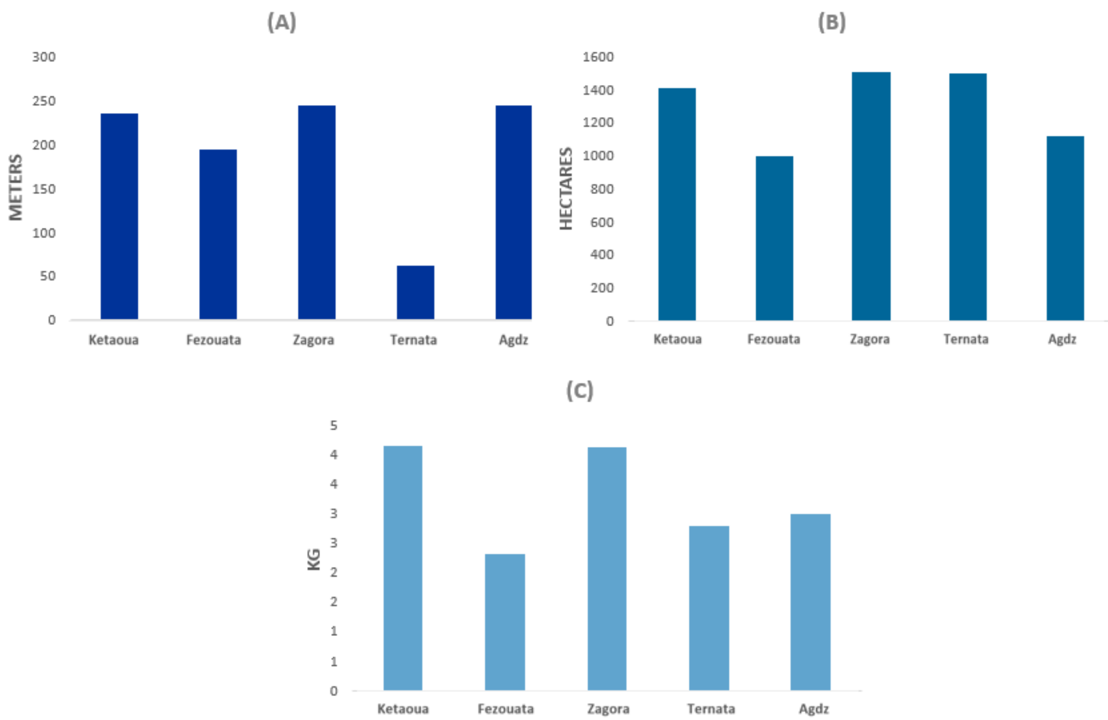

Figure 3.6. The AORC per meter of well dug in graph (A), per hectare of farm in graph (B), and per kg of annual dates produced in graph (C) for each oasis in Moroccan Dirham (MAD).

Figure 3.6 (B) shows that Agdz had the highest replacement costs per hectare of farm, with a mean of 90 MAD, while Fezouata had the lowest. There is no clear pattern when comparing the average loss value per hectare with the total hectares marked in each oasis (Appendix B). We observed that although Fezouata has the highest total number of hectares, it still had the lowest ARC per hectare among all the oases. Our findings suggest that replacement costs across Agdz were generally the highest, not only per hectare of the farm but also per meter dug, in contrast to the other oases where replacement costs were lower on average.

Table 3.1. Total farm hectares and meters dug registered in each oasis.

Oasis	Total farm hectares	Total meters dug
Ketaoua	66	395
Fezouata	134	685
Zagora	59	363
Ternata	85	2024
Agdz	89	407

4.2.3.2. Multiple linear regression analysis

Table 3.2 exhibits the results of the multiple linear regression model (A) (see section 3.4.). The positive and significant regression coefficients for farm size suggest that an increase in farm size is associated with an increase in TRC. None of the oasis's coefficients are statistically significant, indicating that the specific four oases do not have a significant standalone effect on the TRC compared to Agdz as a reference. However, while looking at the interaction terms between farm size and the oases, it is clear that the effect of farm size on the TRC varies across different oases (not for Ketaoua) as compared to Agdz. The positive effect of farm size on TRC is most pronounced in Agdz, and this effect decreases in the other oases, significantly so in Ternata and Zagora. In Zagora, the farm size effect may turn slightly negative, indicating that larger farms there tend to invest a bit less into drilling wells, which could be due to different local conditions or strategies.

Table 3.2. P-value, standard errors, t-statistics, and level of significance for multiple regression model (A) (the dependent variable is TRC; See equation 3.3).

	Coefficient	P-value	t-statistics	Standard errors
Intercept	-36937	0.52	-0.640	57676
Farm size	48824	0.0003 ***	3.751	13017
Oasis Fezouata	90369	0.21	1.246	72502
Oasis Ketaoua	90378	0.33	0.975	92687
Oasis Ternata	125433	0.13	1.504	83386
Oasis Zagora	130403	0.14	1.452	89781
Farm size*Oasis Fezouata	-30888	0.05 .	-1.932	15991
Farm size*Oasis Ketaoua	-36760	0.14	-1.474	24946
Farm size*Oasis Ternata	-39187	0.04 *	-2.033	19274
Farm size*Oasis Zagora	-50073	0.02 *	-2.356	21249
Signifiant codes : 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**				
R^2 = 0.24; Adjusted R^2 = 0.17; F = 3.442 on 9 and 97 DF; p-value = 0.0010 (>0.05=significant model)				

4.2.4. Estimation of the mean digging cost (MDC) at the farm level

Following the MDC formula (see section 3.2.2), figure 3.7 shows a clear overlap in the total variation of the MDC or mean investment to replace lost water between the farms of the five oases. The range of the mean investment within Ketaoua and Agdz's farms is high compared to the rest of the oases. While making up for the losses, the lowest MDC at the farm level during the period 2000-2021 was noted among Ketaoua's farms with 11772 MAD, whereas the highest MDC was marked in Agdz's farms with 136664 MAD.

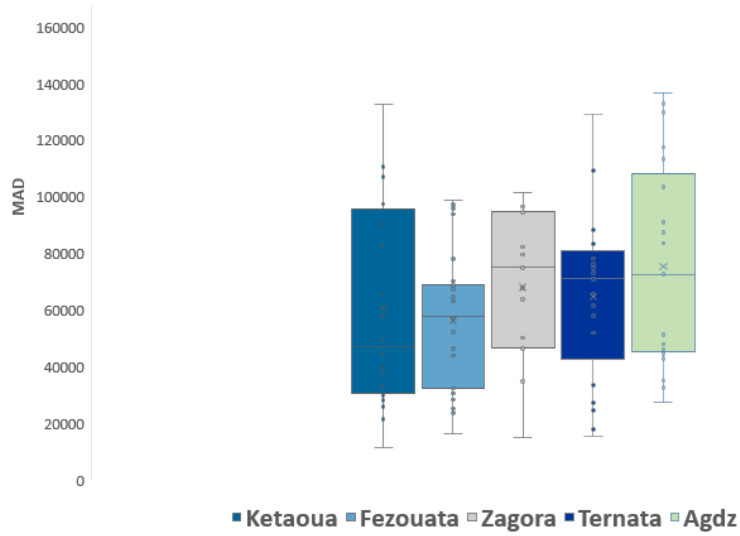

Figure 3.7. MDC in MAD per farm in each of the oases.

4.2.4.1. Mean replacement cost (MRC) per hectare, per meter dug, and per kg of dates produced

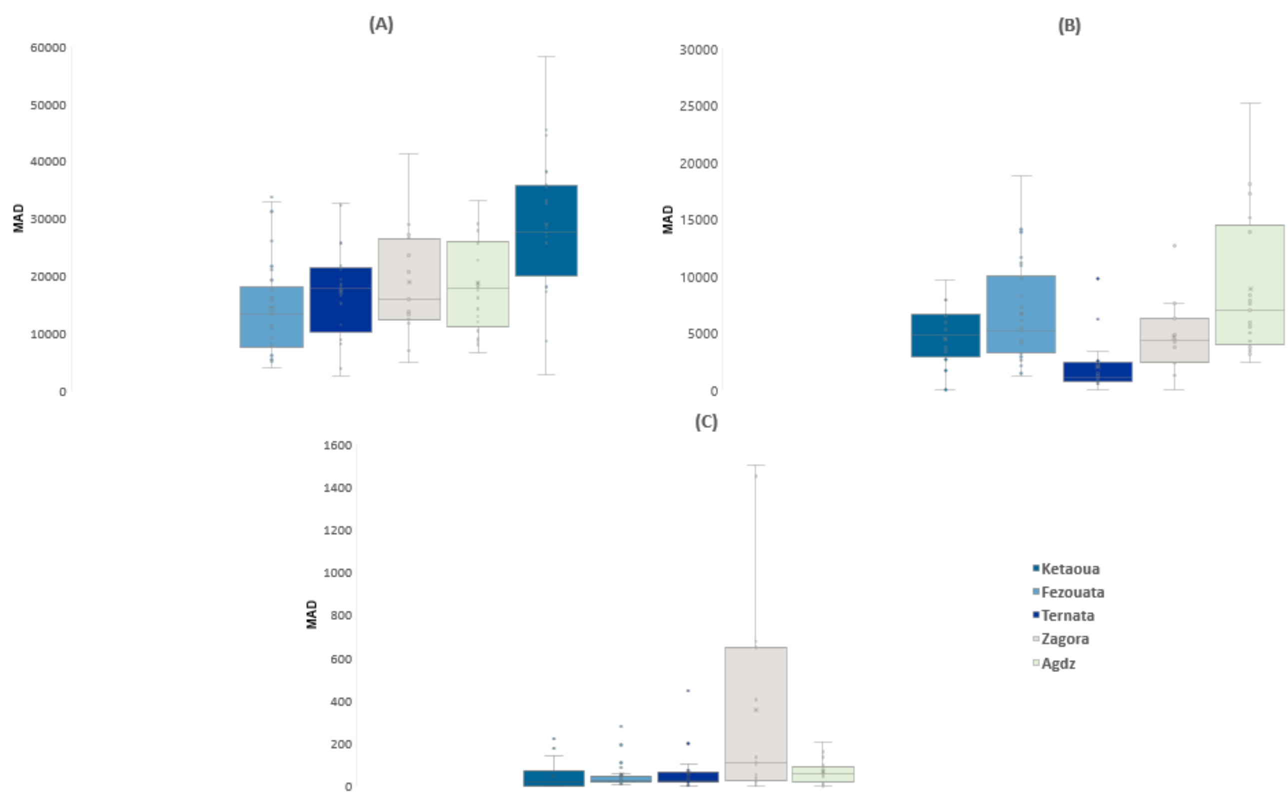

Figure 3.8. MDC (in MAD) per hectare in graph (A), per meter dug in graph (B), and per kg of dates produced (C) at the farm level for the period 2000-2021.

The MRC per hectare of farm

Farmers in Ketaoua and Zagora had the highest range of MDC per hectare invested (Figure 3.8 (A)), despite having smaller farm sizes. In contrast, Fezouata and Ternata had lower ranges of MDC per hectare despite having larger farms (Figure 3.9). This suggests that farms in Ketaoua and Zagora may be experiencing greater losses per hectare compared to larger farms in other oases. The MDC per hectare peaked at 58,182 MAD in Ketaoua during the 2000-2021 period.

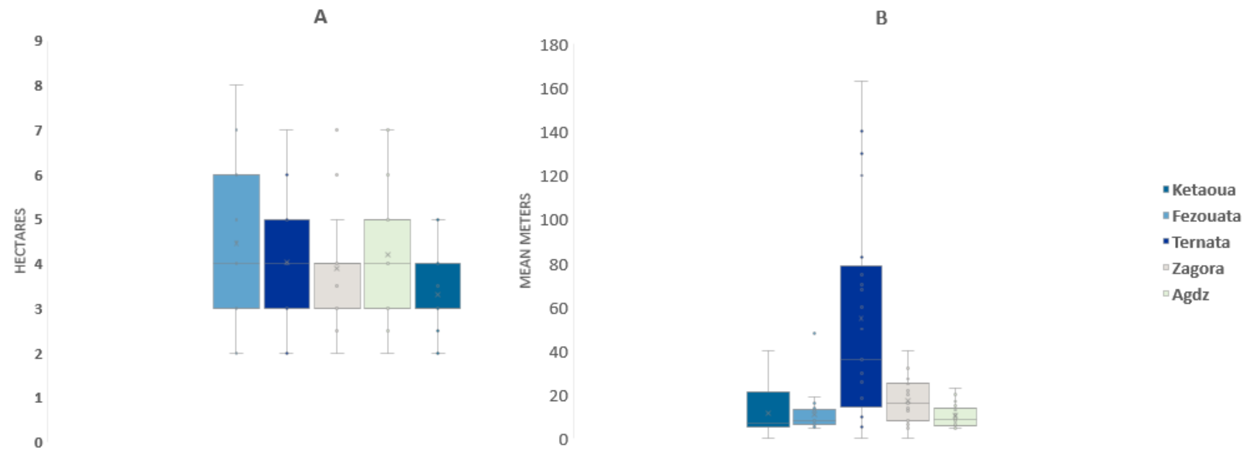

Figure 3.9. Plots showing the farm size ranges in graph (A) and the mean meters dug per farm in graph (B) for each oasis.

The MDC per meter dug

In Figure 3.8 (B), MDC per meter dug overlaps between Ketaoua and Fezouata, and also Zagora and Agdz. Digging costs were high in Ketaoua, Fezouata, and Agdz, where farmers dug less than 48 meters on average (Figure 3.9). In contrast, Ternata, with an average of 163 meters dug, had relatively low replacement costs per meter (Figure 3.9). Farms without wells in Ketaoua, Ternata, and Zagora still invest per meter used from neighboring or collective wells (Figure. 3.8 (B)).

The MDC per kg of dates produced

In Figure 3.8 (C), Zagora shows the highest range of MDC per kg of dates produced at the farm level during 2000-2021. Figure 3.9 reveals that large farms in Fezouata, Ternata, and Agdz invested relatively little per kg of dates produced to replace surface water. Conversely, small farms in Zagora faced greater replacement costs, with the mean loss per kg of dates being the highest at 1,498 MAD. An exception is Ketaoua, where smaller farms also had relatively low investments, with a maximum of 221 MAD per kg of dates produced.

Overall, it appears that large farms, with a high number of hectares, of meters dug, or kilograms of dates produced, invest relatively less than small farms to replace irrigation water sources.

4.2.5. Examining reasons of farmers to invest in water replacement

Table 3.3 presents the results of the regression model (B1) (see section 3.4), which identifies possible factors influencing the total replacement cost per hectare. The negative and significant regression coefficient for farm size indicates that the investment per hectare decreases significantly as farm size increases. The model also shows that the investment per hectare decreases significantly with each additional unit of mean dug within the farm. The coefficient for the annual mean benefit of dates on replacement costs is not a statistically significant predictor in this model. Overall, model (B1) explains only 20% of the variability in the total replacement cost per hectare, which is relatively low.

Table 3.3. P-value, standard errors, t-statistics, and level of significance for multiple regression model B1 (the dependent variable is TRC per hectare of farm).

Model B1 (TRC per hectare)	Coefficient	P-value	t-statistics	Standard errors
Intercept	40430	4.15e-11 ***	7.391	5470.0
Farm size	-2837	0.0403 *	-2.077	1366.0
Mean meters dug	-362.50	0.0046 **	-2.893	125.3
Total meters dug	260.10	0.0024 **	3.104	83.80
Mean annual date benefit	744.60	0.6176	0.501	14.87
Signifiant codes : 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**				
R^2 = 0.20; Adjusted R^2 = 0.07; F = 3.273 on 4 and 102 DF; p-value = 0.014 (>0.05=significant model)				

Results from regression model B2 (Table 3.4) indicate that the mean digging cost (MDC) per meter dug is expected to increase with each unit increase in farm size. However, the significant negative regression coefficient for total meters dug suggests that the investment per meter decreases with each unit increase in mean meters dug. While the mean annual date benefit might explain the increase in investment per meter dug, this coefficient is not statistically significant. The overall model is significant, indicating that at least one predictor is useful in explaining the variance in mean digging costs per meter dug on a farm.

Table 3.4. P-value, standard errors, t-statistics, and level of significance for multiple regression model B2 (the dependent variable is the MDC per meter; see equations 3.4).

Model B2 (MDC per meter)	Coefficient	P-value	t-statistics	Standard errors
Intercept	5062.51	0.000113 ***	4.016	1260.51
Farm size	367.98	0.246	1.166	315.53
Total meters dug	-44.980	0.0000116 ***	-4.610	9.757
Mean annual date benefit	0.0424	0.116	1.243	0.0341
Signifiant codes : 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**				
R^2 = 0.17; Adjusted R^2 = 0.15; F = 7.349 on 3 and 103 DF; p-value = 0.00016 (>0.05=significant model)				

Regression model B3 (Table 3.5) shows the positive significant effects of farm size, mean meters of well dug, and mean annual date production on the mean digging cost (MDC) per kilogram of dates produced by a farm. This cost also decreases significantly for each unit increase of date fruits. The interaction terms between farm size and mean meters dug, as well as between mean meters dug and mean annual date production, are not statistically significant. This indicates that there is no clear combined effect of these variables on the MDC per kilogram of dates produced beyond their individual contributions. Model B3 is significant and explains 11% of the variability in the MDC per kilogram of dates, which is relatively low.

Table 3.5. P-value, standard errors, t-statistics, and level of significance for multiple regression model B3 (the dependent variable is the MDC per kg of date fruits; see equations 3.4).

Model B3 (MDC per kg of dates)	Coefficient	P-value	t-statistics	Standard errors
Intercept	24.67	0.0077 *	2.719	90.73
Farm size	-15.67	0.4946	-0.685	22.86
Mean meters dug	-1.846	0.6824	-0.410	4.500
Mean annual date production	-0.05073	0.00812 **	-2.700	0.0187
Farm size * Mean meters dug	0.3297	0.7675	0.296	1.112
Mean meters dug * Mean annual date production	0.0002443	0.6677	0.431	0.00067
Signifiant codes : 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**				
R^2 = 0.11; Adjusted R^2 = 0.06; F = 2.567 on 5 and 101 DF; p-value = 0.03139 (>0.05=significant model)				

Finally, in model C (Table 3.6), the analysis shows that there is a notable impact of the mean annual date production and benefit on the total replacement cost (TRC). The negative coefficient associated with the mean annual production implies that as the farm produces more dates annually, the total replacement cost decreases. This suggests that higher quantities of dates tend to lower the overall replacement costs. However, the positive coefficient linked to the benefit from dates indicates that as revenue from date sales increases, so does the expenditure on accessing or improving access to groundwater.

Table 3.6. P-value, standard errors, t-statistics, and level of significance for multiple regression model C (the dependent variable is the TRC; equation 3.5).

Model C (TRC)	Coefficient	P-value	t-statistics	Standard errors
Intercept	48324.3	0.0527 .	5.207	24660
Farm size	19509.11	0.00160 **	1.356	6016.07
Mean annual date production	-28.24	0.0025 **	3.378	9.128
Mean annual date benefit	3.397	0.00281 **	0.267	1.110
Signifiant codes : 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**				
R^2 = 0.24; Adjusted R^2 = 0.17; F = 8.656 on 3 and 103 DF; p-value = 0.000035 (>0.05=significant model)				

4.2.6. Mean reduction in production of wheat, alfalfa, and livestock

Farmers were asked to report the reduction in wheat, alfalfa, and livestock production due to changes in water availability. For that, we took the difference between what they produced before and after the water changes occurred. The highest reduction in wheat harvest was observed in Zagora with a decrease of 33.74%, while the lowest was in Fezouata with a decrease of 16.65%. Fezouata also had the highest reduction in the number of alfalfa plots, decreasing almost 30% in each farm. Farmers in Zagora had the highest percentage reduction in the number of cattle they owned, with a decrease of 18% compared to the other oases. Figure 3.10 shows that farmers experienced an important reduction in date production (quantities and related benefits).

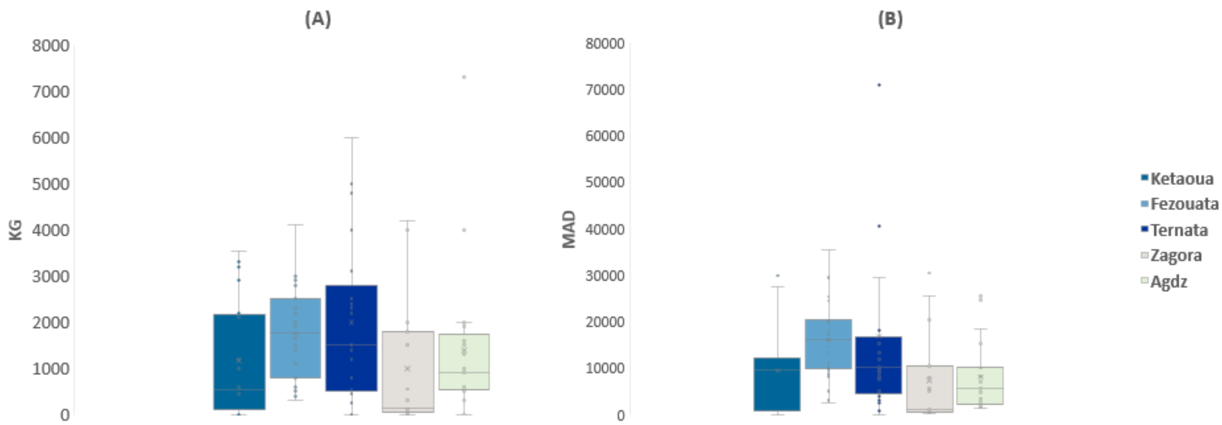

Figure 3.10. Mean annual quantities of dates (A) and benefits of dates (B) lost over the period 2000-2021.

4.2.7. The level of improvement after the replacement

We surveyed 107 farms to assess their improvements after implementing technical substitutes for their agricultural water supply. The majority, 97%, reported recovering only half of their previous water supply, leading to producing two to three times fewer crops like dates, wheat, barley, and alfalfa. In contrast, only 3% of the farms fully recovered their water and crop levels. The 97% included small and medium-scale farmers who mainly dug and deepened wells, with 23% also building basins. The 3% that achieved full recovery primarily used a combination of tube wells, water basins, and solar energy pumps for irrigation.

4.3. Discussion

4.3.1. The Total loss value (TRC)

Our original hypothesis (1) suggested that changes in water availability would lead to varying losses across the oases of the MDV, increasing from north to south along the aridity gradient. Consequently, investments to offset these losses would follow a similar pattern. Our results confirmed the first part of the hypothesis but showed that losses did not consistently increase or decrease with the aridity gradient of the MDV (Figures 3.4 and 3.5). Instead, they fluctuated. Our multiple regression model A (see section 3.5.3) indicates that losses along the valley fluctuate due to farm size and other unknown factors. Larger farms tend to invest more to replace lost surface water, resulting in greater average losses compared to smaller farms. This may be due to their higher investment capacity, access to new technologies (e.g., irrigation, water pumping), and subsidies. Prior research on climate change adaptation in agriculture supports this (Al-Tawaha *et al.*, 2022). Smaller farmers might adapt more easily by diversifying income sources, whereas larger farmers rely more heavily on farming. Our regression analysis revealed that the effect of farm size on total replacement investment varies across the different oases (Fezouata, Ternata, and Zagora). While farm size generally has a positive impact on the replacement cost of farms, this effect diminishes in these oases. This reduction may be related to their ability to invest from alternative income sources or significant remittances. Additionally, the hydrological and geospatial attributes of these oases, as discussed by Dekkaki *et al*. (2023), could explain the differing effects of farm size on expenditures. In Zagora, the results even suggested that larger farms might invest less in digging activities, possibly due to local conditions or economic factors such as lower returns from farming. Variations in farmers' perceptions of irrigation water scarcity across the MDV may explain the fluctuating losses, as prior behavioral economics research suggests (Shogren and Taylor, 2008; Robinson and Hammitt, 2011). Other studies highlight additional factors such as proximity to water reservoirs and diversity of income-generating activities that influence farmers' investments in irrigation water during scarcity (Acquah and Onumah 2011; Chen *et al*. 2018; Fan *et al*. 2019; Uddin *et al*. 2014). However, this analysis only briefly covers these factors. Losses from changes in water availability varied across the MDV between 2000 and 2021 and did not consistently increase in regions with higher aridity. This finding does not imply that drought did not contribute to these losses but rather indicates that other factors (e.g., farm size, oasis location) also influence the impact of water scarcity, even in less severely affected areas. Specific aspects of the Fezouata oasis significantly determine the average expenses farmers incur to secure alternative water sources. This highlights the importance of these characteristics in agricultural practices and water management strategies, warranting further research.

4.3.2. The Mean loss value (MDC) at the farm level

The cost of replacing lost surface water is similar across different oases (see section 3.5.4). As a first interpretation, we assume that farms with higher investments on average may experience more losses than those with lower investments. However, we hypothesized (2) that for large farms with more production, hectares, or deep wells, the cost of replacement is relatively cheaper, resulting in a lower potential loss value per unit of farm area compared to small farms. This relative cost advantage means that larger farms may have an advantage in terms of economies of scale, as they can spread their fixed costs over a larger output or productive area, resulting in lower replacement costs per unit of production or area. This was mainly displayed by the regression models B1, B2, and B3 for the TRC per hectare, the MDC per meter, and kg of dates. Shan et al (2015) as well as Lapar et al (2012) similarly stated that larger farms have lower production costs per unit of output and are more technically efficient than smaller farms (see also Alston *et al*. 1998; Barkley *et al*. 1999). Mafoua (2002) stated that tow-crop farms, as well as three-crop farms, exhibit overall economies of scale that increase with the farm size, as they can lower the cost of producing crops in the same farm by spreading fixed and variable costs over their large output, compared to small farms. Therefore, the ability to invest in deeper wells in a single event could explain the difference in replacement costs between larger and smaller farms, leading to differences in water loss. Accordingly, a single efficient digging event may offer greater benefits than multiple events. Ho and Shimada's (2019) research in India suggests that larger farms are more efficient in their groundwater use due to their ability to invest in efficient irrigation technologies, resulting in lower losses and greater cost-effectiveness compared to smaller farms. While investing more in replacing surface water may result in overall higher losses, large-scale farms enjoy economies of scale, allowing them to minimize losses per unit of surface and meter dug.

4.3.3. Reasons explaining farmers' investment to replace lost surface water

Farmers' investment strategies in the MDV to access more irrigation water differ according to a few factors. Our findings show that the overall investment of farmers increases with increasing farm hectares and mean meters dug. One explanation is that larger farms can invest more and require more water due to larger cropping areas. Higher annual benefits from growing dates may explain the additional investment in irrigation water. This was displayed by the regression model (C) (see section 3.5.5). More precisely, as the farm produces more dates, the TRC decreases. Conversely, as the benefits from date production increase, the total replacement costs also tend to increase. The negative correlation could be because higher date quantities might lead in certain cases to economies of scale or more efficient use of resources, reducing overall costs. During the interviews, we learned that part of the dates produced are sometimes stored and only sold later when market prices are favorable. This might explain the decreased expenditure to improve or replace irrigation water sources. The storage of dates also allows for an extended selling period, according to the interviewees, and preserves their quality, which maximizes the revenues from dates. Profits from better-timed market sales due to storage can be reinvested into improving groundwater access and irrigation infrastructure, which may initially increase irrigation costs. This explains the positive effect of benefits on the TRC. Similar findings from Greiby and Fennir (2023) as well as Navarro and Navarro (2015) discussed post-harvest handling of date fruits and its effects on farming costs in semi-arid ecosystems. In addition, the findings of a study by Kiprop et al. (2017) with farmers in Kenya concluded that crop income from irrigation significantly influences farmers' decisions to pay for irrigation water.

The survey identified two potential factors that could affect farmers' investment in irrigation water for further investigation. First, farmers who rely exclusively on groundwater for irrigation may be more willing to pay for water, possibly due to its perceived reliability as a consistent water source, compared to those who use both groundwater and dam releases. This is consistent with the work of Biswas and Venkatachalam (2015) who concluded that farmers are willing to spend more on irrigation water if they can predict water availability (see also Bouman 2007). Second, household size may also impact farmers' willingness to invest in irrigation water. Larger families may be less willing to invest in irrigation water due to high engagement in non-agricultural activities. Alternatively, larger families may rely more heavily on remittances from family members working outside the area. This is supported by the findings of Tang et al. (2013) in a similar study with farmers within the Chinese Loess Plateau, agricultural practices and the sustainable rural livelihoods factors(see also Arshad *et al*. 2016; Gebretsadik and Romstad 2020; Mustapha 2012). The individual discount rate may also influence the investment decisions of farmers, as when it's high, it could make future costs and benefits associated with water replacement appear less valuable compared to immediate costs, thus increasing the willingness to invest to replace this water. Conversely, a lower discount rate may result in a longer asset lifecycle and slower technological progress. While the impact of the individual discount rate on farmers' investment is important, it was not the primary focus of the present paper. In summary, our findings highlight the complex interplay between farm size, perceived benefits of crops, and irrigation infrastructure investment in agricultural production. Further research could explore these factors more deeply, as well as examine potential policy implications for promoting sustainable and efficient water use in agriculture.

4.3.4. Evaluating the replacement cost approach: Application and valuation outcome

We used the RCA to estimate losses in the MDV oases due to water availability changes and gain insights into farmers' behavior in adopting technical alternatives. The RCA method was effective in partially achieving this goal. Our working assumption was that money spent on obtaining additional water was indicative of losses suffered from reduced irrigation water. The AORC and MDC provided reliable estimates for the loss values. However, we believe our estimates undervalued the ecosystem service loss value from reduced surface water availability. This was mainly because our analysis only covered detailed costs related to date production, benefits, and crop production reduction, and other crops such as Alfalfa, wheat, and livestock were not quantified in the same way. Most of these products were mainly exchanged in nature and used for subsistence, and therefore hard to quantify. To make a proper and accurate estimation of the ecosystem service loss, it is crucial to quantify the non-recovered crops.

While other methods, such as the defensive expenditure method, can also estimate loss value, we deemed the RCA method more suitable for our analysis (Sundberg, 2004b). It is worth noting that although the RCA method has been used in other contexts, it has not been utilized to estimate loss values due to lost ecosystem service elements. Therefore, there was no previous reference to compare the application of the RCA method in this particular context. This lack of similar applications could have potentially affected the accuracy and reliability of our results. Testing the Replacement Cost Approach here revealed significant insights. While our goal was to accurately assess ecosystem service losses, we found that these losses cannot simply be compensated by digging wells, and other motivations might drive this action.

The RCA requires extensive historical data for accurate loss estimation, and our findings highlight its limitations and applicability. Estimating costs from 20 years ago proved to be a challenge, particularly when dealing with farmers who had no written records of their expenses. The meticulousness in bringing past information and numbers into sharp focus played a vital role in producing highly reliable results. Our work, amidst a scarcity of comparable studies, provides valuable information for future research on RCA and ecosystem service loss estimation.

4.4. Conclusion

Our analysis demonstrates the potential and shortcomings of using the replacement cost method (RCA) to value the losses of ecosystem services experienced by farmers in the Drâa Valley, Southern Morocco, due to lost surface water availability in the past decades. We estimated the costs farmers incurred to invest in technical installations (wells) to replace the decreasing irrigation water availability in the Drâa River. Those replacement costs reflect the value of irrigation water in the area. We identified how farmers reacted to surface water reduction and showed the differences among and within oases through cost assessments. However, the lack of essential quantifiable data, mainly for non-recovered crops and cattle, limited the accuracy of our estimations. This information can be a valuable tool for understanding and forecasting farmers' behavior and reasoning under water scarcity assuming their varying utility and helps understand how they may be willing to adapt to changes in water availability as future water deficits increase. Contrasting the losses experienced by farmers across different oases in a water scarcity context can help identify the areas suffering the most. In addition, the analysis showcases that large farms may have an advantage in terms of economies of scale, as they can spread their costs over a larger output or productive area, resulting in lower replacement costs per unit of production or area. Understanding the implications of an economy of scale on water management and production costs can be crucial for policymakers, farmers, and researchers. This can also contribute to developing water allocation incentives and programs to support effective water resource management, particularly for small farmers, as those are often neglected in research on water scarcity and agricultural development (Perret and Stevens 2006). Our results highlight the factors playing an important role in shaping the impacts of water scarcity on farmers. This can help inform policymakers and stakeholders focusing on promoting sustainable and efficient water use in agriculture, considering the complex interplay between various factors.

This paper contributes to the literature on ecosystem services valuation by providing a practical example of how the RCA method can be used to estimate the value of lost ecosystem services, such as irrigation water supply. By using this method, we were able to gain valuable insights into the socio-economic impacts of water scarcity on rural communities in semi-arid countries. However, further studies and applications of economic valuation methods with similar objectives are necessary to compare and improve the approach and obtain better outputs. Our research can inform future studies on ecosystem services valuation and its implications for sustainable development. Overall, the present analysis provides insights into the socioeconomic impacts of water scarcity on rural communities in semi-arid countries and can further contribute to a better understanding challenges they face. It also provides insights into the potential strategies and policies that can be developed to promote sustainable water resource management and enhance agricultural productivity in water-scarce regions. The analysis underscores the need for more applications of economic valuation methods that can contribute in this sense.

Chapter 4

Water quality, biological quality, and human well-being: Water salinity and scarcity in the Drâa River Basin, Morocco

Nils Kaczmarek[a,] Imane Mahjoubi[a,] Mokhtar Benlasri[b,] Maren Nothof[c,] Ralf B. Schäfer[a,] Oliver Frör[a,] Elisabeth Berger[a]

[a] iES Landau (Institute for Environmental Sciences), RPTU Kaiserslautern-Landau, Landau, Germany.

[b] Research Center of the Museum of Natural History, Cadi Ayyad University, Marrakesh, Morocco.

[c] Molecular Ecology Group, RPTU Kaiserslautern-Landau, Kaiserslautern, Germany.

Adapted from the manuscript published in Ecological Indicators (ELSEVIER) in 2023. 148, 6276. 10.1016.2023.110050.

4.1. Highlights

- Positive correlation between river water quality and biological quality
- Poor biological quality associated with high conductivity and low water flow
- Poor human satisfaction associated with high water temperature and conductivity
- Water salinity and scarcity cause emotional distress
- Measures to improve well-being should consider ecosystem/people interdependence

4.2. Abstract

River ecosystems are being threatened by rising temperatures, aridity, and salinity due to climate change and increased water abstractions. These threats also put human well-being at risk, as people and rivers are closely connected, particularly in water-scarce regions. We aimed to investigate the relationship between human well-being and biological and physico-chemical river water quality using the arid Drâa River basin as a case study. Physico-chemical water measurements, biological monitoring of aquatic macroinvertebrates, and household surveys were used to assess the state of the river water, ecosystem, and human well-being, as well as the associations between them. Salinity levels exceeded the maximum permissible values for drinking water in 35 % and irrigation water in 12 % of the sites. Salinity and low flow were associated with low biological quality. Human satisfaction with water quantity and quality, agriculture, the natural environment, and overall life satisfaction were low, particularly in the Middle Draa, where 89% of respondents reported emotional distress due to water salinity and scarcity. Drinking and irrigation water quality was generally rated lower in areas characterized by higher levels of water salinity and scarcity. The study found positive associations between the river water quality and biological quality indices, but no significant association between these factors and human satisfaction. These findings suggest that the relationship between human satisfaction and the biological and physicochemical river water quality is complex and that a more comprehensive approach to human well-being is likely needed to establish relationships.

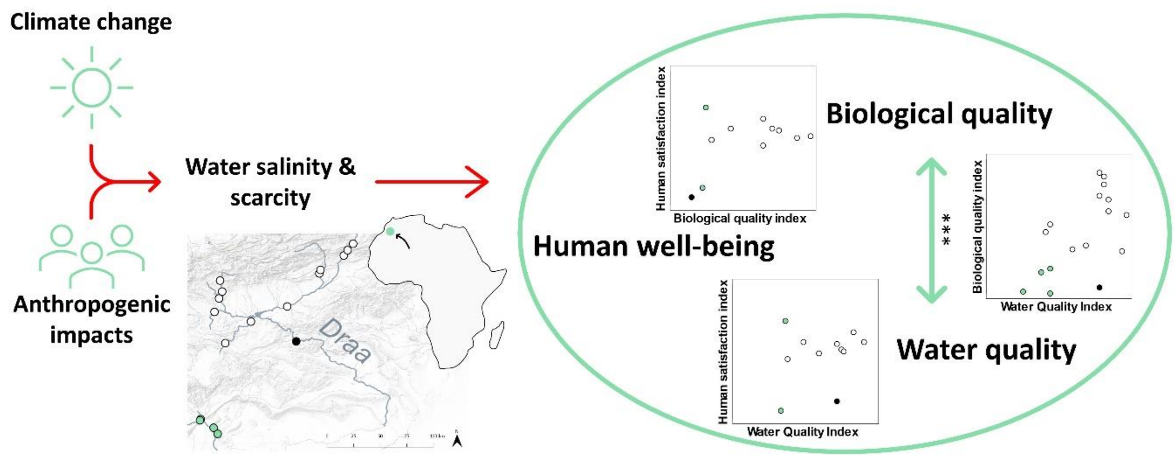

Figure 5.1. Graphical Abstract for Chapter 4.

4.3. Introduction

In the past 50 years, the framing of nature conservation developed from conserving nature for its own good, to conserving nature for the benefit of people, to a shared human-nature environment (Mace, 2014). In this social-ecological system perspective, human well-being is linked directly to the health of the ecosystem and includes the mental and physical health of individuals (Andrews and Duff, 2020), the social bonds between them, but also the relationship between humans and nature (Gergen, 2009). This implies that human well-being is related to the quality of resources and ecosystem services and consists of the fulfillment of different interdependent categories of material and non-material needs (Gergen, 2009; Mace, 2014). The access to nature and the existence of biodiversity in the vicinity was shown to increase well-being (Hartig et al., 2014; Marselle et al., 2019). Understanding the direct and indirect connections between ecosystem health and human well-being and satisfaction can deliver crucial insights that may inform future conservation efforts.

River ecosystems play a vital role in human well-being by providing freshwater and food, regulating climate, and offering cultural services (Akinsete et al., 2019). However, human activities such as hydromorphological changes, pollution, as well as changes in climate conditions increase salinity levels and can threaten human well-being (Akinsete et al., 2019; Cunillera-Montcusí et al., 2022). River ecological health (i.e., river water quality, water quality influencing factors, status of the river ecosystem) and human well-being were decreasing from up- to downstream in a study using the Happy River Index in China, where water scarcity, degradation of the ecosystem, soil erosion, and pollution, and unguaranteed ecological flow were restricting human well-being and ecosystem health (Zuo et al., 2020). Nature and riverscapes can impact mental and physical health (Kaplan 2001; Russell et al., 2013; White et al., 2010), with studies reporting a positive correlation between river naturalness and human well-being (White et al., 2010). Disconnectedness from nature can have negative effects on psychological health (Frumkin et al., 2017; Kals & Maes 2004; Sandifer et al., 2015). However, most studies have been conducted in developed countries and focused on large perennial rivers (Cruz-Garcia et al., 2017). It remains open to which extent this can be extrapolated to intermittent, ephemeral, and dry rivers in countries of the Global South (Ferreira et al., 2022; Messager et al., 2021; Nicolás-Ruiz et al., 2021). As climate change and anthropogenic pressures continue to increase, these systems and regions may be particularly threatened by deteriorating ecological and human health (Liu et al., 2022; Zou et al., 2020).

In the Drâa River basin in the South of Morocco, people depend directly on the river ecosystem, as it provides water for irrigation and domestic use, and thus helps to survive in the arid conditions of the northern Sahara (Mahjoubi et al., 2022). In the upper reaches of the Drâa River basin, salinity is primarily caused by geological factors, with rocks and soils releasing ions into the water (Warner et al., 2013). Depending on the rock types, some streams have salinity levels as high as 20 mS/cm (e.g., El Mellah River; direct translation: Mellah = salt), almost half the level of seawater. Salinity further increases, especially in the Middle and Lower Drâa basins, due to lower rainfall and increasingly arid climate (Beck et al., 2018; Williams, 1999), which leads to a lack of dilution of water and high evaporation, respectively (Warner et al., 2013). Secondary salinization, such as the use of saline freshwater for irrigation (Hssaisoune et al., 2020; Williams 1999) in the large date palm oases along the Middle Drâa (Karmaoui et al., 2014), further increases salinity (Haj-Amor et al., 2016). The drying of intermittent streams during the summer and changes in the natural flow regime caused by the presence of a large dam between the Upper and Middle Drâa impose additional stress on the river ecosystem (Karmaoui et al., 2014). The Drâa River basin is characterized by several aridity and salinity gradients that allow to study of associations between these gradients and potential responses of the river ecosystem and human well-being (Johannsen et al., 2016).

We assessed how river water quality and biological quality of rivers are associated with water salinity and scarcity in the Drâa River basin and how these relate to human well-being. River water quality was assessed through physico-chemical water quality parameters to describe the state of rivers. Aquatic macroinvertebrate metrics were used to describe the biological quality, as macroinvertebrates fulfill important roles in the functioning of freshwater ecosystems and their presence in most aquatic habitats makes them suitable for studying the biological quality of rivers (Wallace & Webster, 1996; Covich et al., 1999). Human well-being was assessed through a standardized household survey targeting the topics of water and crop quality, people's health status, and satisfaction.

Based on the processes of primary and secondary salinization and their effects on the river ecosystem, we propose the following hypotheses: High water salinity is associated with (1) poor river water quality and (2a) low biological quality of rivers. We also expect (2b) reduced flow rate as a measure of water scarcity to be associated with low biological quality. Additionally, we hypothesize (3) human satisfaction to be associated with low river water and biological quality, as we expect a direct link between the river ecosystem and human well-being. These hypotheses were tested by analyzing the relationships between river water quality, biological quality, and human well-being indices.

4.4. Material and Methods

4.4.1. Study area

A total of 17 sites in the Drâa River basin were selected for the assessment of river water and biological quality and visited in October 2021 and March 2022 (Figure 4.2; Table S 4.1). 13 of those sites were in tributaries originating in the High and Anti-Atlas Mountains that drain into the El Mansour Eddahbi dam. From there the Drâa River flows southeast, here referred to as Middle Draa, before turning as Lower

Drâa towards the Atlantic Ocean. However, the Middle and Lower Drâa are dry for most of the year, leading water only after heavy rainfall events or dam releases. Only one site was selected in the Middle Draa because the dry state of the river during the study period did not allow further ecological assessments of aquatic macroinvertebrate life stages. Four sites were located in the Lower Drâa sub-basin at a tributary from the Anti-Atlas.

Surveys with residents were conducted in October and November 2021 and April 2022, interrupted by a nationwide lockdown. Sites were located in 11 localities close to the ecological sites and in three further localities along the Middle Draa, where no ecological sites were located due to the dry state of the river during the study period, which resulted from a two to three years long drought (Figure 4.2).

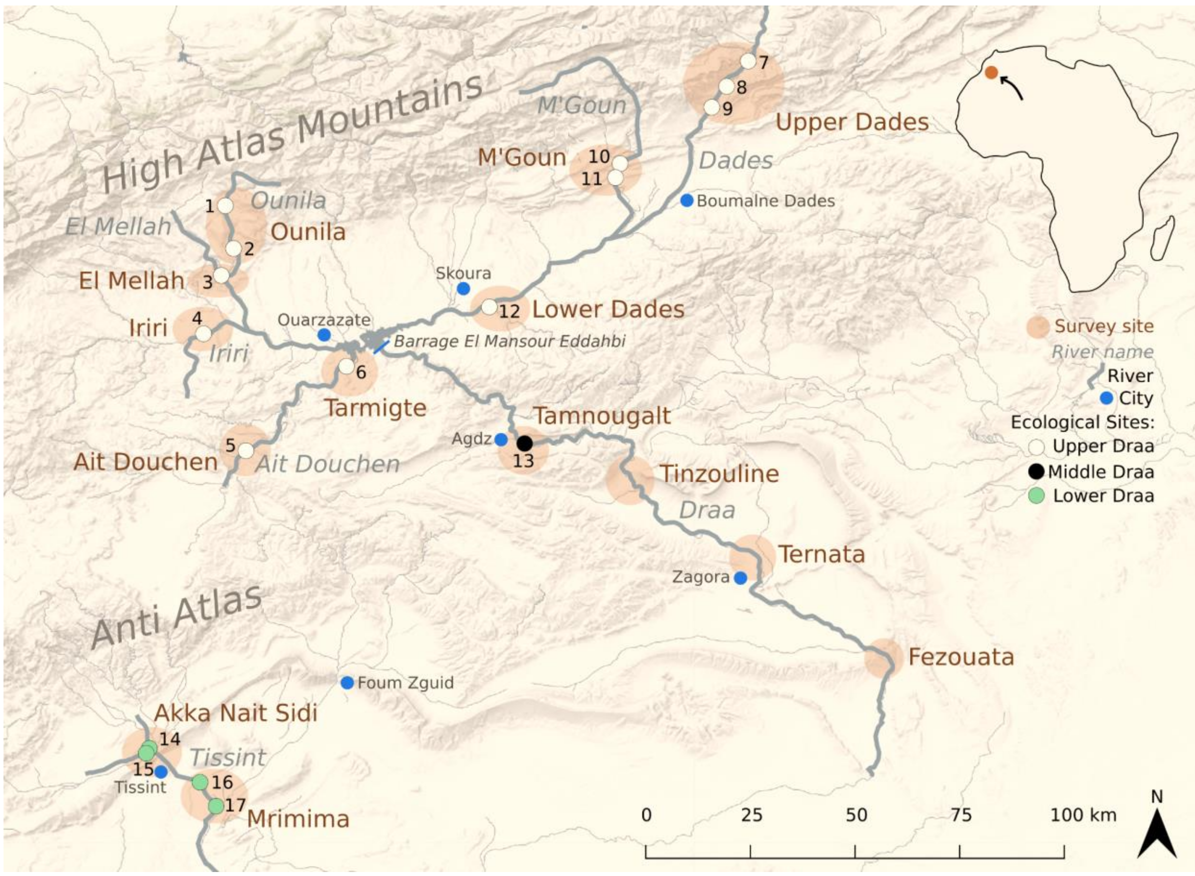

Figure 5.2. Map of Drâa River basin showing the 17 ecological study sites and 14 survey sites. Ecological sites in ellipses were assigned to survey sites. (terrain-basemap: © EOX).

4.4.2. Physico-chemical parameters

Water temperature, pH, electrical conductivity, and dissolved oxygen were measured by using a multi-parameter (WTW MultiLine® Multi 3510 IDS) in the 17 ecological study sites (Figure 4.2). Furthermore, river width and depth were measured. Flow velocity was measured using a hydrological impeller (SEBA Hydrometrie) and subsequently combined with the area of the cross profile to calculate the flow rate. The ion composition was measured in the field by using the MACHEREY-NAGEL VISOCOLOR reagent case with the photometer PF-12Plus and VISOCOLOR Eco colorimetric test kits. Measurements covered chloride

(Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), orthophosphate (PO_4^{3-}), potassium (K^+), total hardness (TH) and carbonate hardness (CH). Concentrations of nitrate, nitrite, ammonium, orthophosphate, and potassium lower than 4, 0.02, 0.01, 0.6, and 2 mg/l, respectively, were below detection level. Concentrations of chloride above 6,000 were set to 6,000 as these stands for the upper water quality standard boundary and we refrained from higher dilution of samples for measurements to avoid inaccuracies. To account for temporal variability and measurement errors in data analysis, the measurements from October and March were averaged (except for dissolved oxygen and nitrite which were only measured in October). If a value was under detection level, we used half of the detection level to calculate the mean, a method commonly used (Uh et al., 2008, but see Clarke, 1998). Although more advanced methods are available, in our case with only a few non-detects and few sites, the bias was supposed to be low (Helsel, 2006; Helsel, 2010). In the case of sulfate, we excluded two outliers as they were more than 18 times higher than the values of all other sites including previous measurements in the same sites. We attributed these outliers to measurement errors. Values were compared to Moroccan water quality standards for drinking water (Royaume du Maroc, 2006) and irrigation water (SEEE, 2007) to evaluate the exceedance of maximum admissible values.

4.4.3. Water quality index

A river water quality index, hereafter WQI, was calculated to determine river water quality using a modified version of the Moroccan water quality index (Royaume du Maroc, 2008). We did not quantify 5-day biochemical oxygen demand (BOD_5), dissolved organic carbon (DOC), total phosphorus, and fecal coliforms, which are used to evaluate the water quality of rivers in Royaume du Maroc (2002) while quantifying water temperature, pH, electrical conductivity, chloride, sulfate, and nitrate, which are described in Royaume du Maroc (2002) for the assessment of water quality. Dissolved oxygen and ammonium were included as in the original index. All parameters were scaled to a range from 0 to 100 using the class boundaries and calculation as described in Royaume du Maroc (2002 & 2008; Table 4.1). For sulfate, nitrate, and ammonium, the minimum values were set to half the detection level (sulfate <20 = 10; nitrate <4 = 2; ammonium <0.1 = 0.05), other parameters had all values above the detection level.

Table 5.1. Moroccan water quality standards and intervals (Royaume du Maroc, 2002 & 2008) for the used parameters water temperature (Temp), pH, electrical conductivity (Cond), dissolved oxygen (Oxygen), chloride, sulfate, nitrate, and ammonium.

Classificat-ion	WQI	Temp [°C]	pH	Cond [µS/cm]	Oxygen [mg/l]	Chloride [mg/l]	Sulfate [mg/l]	Nitrate [mg/l]	Ammonium [mg/l]
Excellent	100 - 80	0 - 20	6.5 - 8.5	100-750	7 - 10	0 - 200	0 - 100	0 - 10	0 - 0.1
Good	80 - 60	20 -25	-	750 - 1300	7 - 5	200 - 300	100 - 200	10 - 25	0.1 - 0.5
Moderate	60 - 40	25 - 30	8.5 - 9.2	1300 - 2700	5 - 3	300 - 750	200 - 250	25 - 50	0.5 - 2
Bad	40 - 20	30 - 35	3.5-6.5, 9.2-10	2700 - 3000	3 - 1	750 - 1000	250 - 400	> 50	2 - 8
Very bad	20 - 0	35 - 40	-	3000 - 7000	1 - 0	1000 - 6000	400 - 2000	-	8 - 50

4.4.4. Biological quality

4.4.4.1. Macroinvertebrates

At each ecological site, macroinvertebrates were sampled by using a 33 x 31 cm (0.1 m^2) Surber sampler (mesh size 500 µm) in October 2021. Quantitative samples were taken at ten spots per site which were selected to cover all microhabitats based on the proportion of microhabitats in a 100-m reach, resulting in a sample area of 1 m^2 per site. The samples were conserved with 95 % ethanol until sorting and identification of taxa in the laboratory. Taxa were identified to species level, except for Diptera (family or subfamily), Odonata (family or genus), Crustacea (order or species), Mollusca (genus or species), Annelida (sub-class), and Tricladida (class).

Macroinvertebrate metrics describing biodiversity: taxon richness (number of taxa) and percentage of taxa of the orders EPT (%EPT; Ephemeroptera, Plecoptera, and Trichoptera), and multi-metric biotic indices describing the biological water quality: IBMWP (Iberian biological monitoring working party, Jáimez-Cuéllar et al., 2002) and IBGN (Indice Biologique Global Normalisé, Archaimbault & Dumont, 2010), were calculated to describe biological quality of the rivers. These metrics have already been used in Morocco before (Feio, 2021). However, sampling methods differed from the protocols used for IBMWP and IBGN.

4.4.4.2. Biological quality index

We created a biological quality index (BQI). Therefore, we normalized the macroinvertebrate metrics (taxon richness, %EPT, IBMWP, IBGN) to a scale from 0-100 to match the WQI and calculated the mean of the metrics per site, to compare it to the other indices and to analyze the impact of physicochemical parameters on the biological quality of rivers.

4.4.5. Human well-being

To compare people's perception of drinking and irrigation water quality, their health, and satisfaction, 181 interviews using a structured standardized questionnaire were conducted with residents in the 14 survey sites (Figure 4.2), ranging from 7 to 23 interviews per site which lasted 5 -12 minutes. Respondents were selected randomly. The survey used a mixed qualitative-quantitative research approach using categorical multiple choice questions to identify the water sources used for drinking and irrigation, single-answer multiple choice questions to cover the perceived quality of river water, groundwater, and the produced crops in relation to different sources of water (river water, groundwater, ONEE (The National Office of Electricity and Drinking Water) tap water or truck delivered water), and rating scales to assess the effect of water quality and quantity on people's health status, and six aspects of satisfaction (health care, quantity and quality of water resources, agricultural production possibilities, conditions of the natural environment, and life overall). We additionally asked for gender, occupation, and age categories (Table S.2) to check for differences in responses between these categories.

To calculate a human satisfaction index (HSI) we used the values of the responses to the 4-point scale questions on satisfaction with health care, quantity and quality of water resources, agricultural production possibilities, and the conditions of the natural environment, ranging from very unsatisfied to very satisfied for the 14 survey sites applying equal-weights. Satisfaction with life overall was not used to calculate the index, as it represents already an aggregate measure of satisfaction. Individual respondent HSI values were taken to calculate a mean HSI per site (Figure 4.1). We normalized the index to a scale from zero (very unsatisfied) to 100 (very satisfied) to compare it to the other indices. We analyzed the impact of physico-chemical parameters on the mean HIS values per site to check for possible associations.

4.4.6. Data analysis

For all data analyses we used R v.4.0.4 (R Core Team, 2021) and RStudio (version 1.2.5019) with the package “car” (Fox et al., 2007), “dplyr” (Wickham et al., 2015), “rstatix” (Kassambara, 2020), “caret” (Kuhn, 2009), and “beanplot” (Kampastra, 2008).

Before regression analysis, we excluded the predictors nitrite, ammonium, and carbonate hardness, as most values were either the same (i.e., very low variance) or below the detection limit. Sulfate was excluded because of two errors as mentioned above. We omitted chloride ($r = 0.93$), potassium ($r = 0.89$), and total hardness ($r = 0.82$) due to a high bivariate correlation with electrical conductivity (Dormann et al., 2013). To analyze the associations between physicochemical parameters (i.e., water quality), biological quality, and human satisfaction, we employed the regularized regression method elastic net that simultaneously does variable selection and shrinkage of regression parameters. The elastic net can be viewed as a generalization of the lasso with a combination of the lasso and ridge penalty (Zou & Hastie, 2005). This regression method can be used even if the ratio of observations (17 sites) to predictors (6; flow rate, water temperature, pH, electrical conductivity, dissolved oxygen, and orthophosphate) is low (Zou & Hastie, 2005). To check for significant differences in the survey responses between the survey sites and between demographic groups (i.e., gender, occupation, and age), we used the response values for the perceived quality of drinking water, irrigation water, and crop production, as well as mean satisfaction for each site. We used ANOVA for homogeneous and Welch’s ANOVA for heterogeneous variances, followed by a Tukey's HSD or Games-Howell post-hoc test, respectively. Associations between WQI, BQI, overall satisfaction HSI as well as its elements were analyzed using Pearson’s and Spearman’s correlation coefficients. See Figure 4.1 for the match between ecological and survey sites.

4.5. Results

4.5.1. River water quality

River water quality, as defined by the WQI, was good in 16 and moderate in one site (Table S 4.1). Water quality was lowest in the Lower Drâa (Figure 4.2), and two tributaries in the Upper Drâa. Low WQIs were mainly caused by very high electrical conductivity levels exceeding maximum admissible values by Moroccan water quality standards for drinking water (MAVDs) in six, and for irrigation water (MADIs) in two of those sites (Figure 4.3). Chloride exceeded MAVDs and MADIs in all sites, with the highest values in the same abovementioned sites, while pH exceeded both standards in two sites (Figure 4.3). Sulfate exceeded MADI in one site. All other parameters met water quality standards, with values often close to or under the detection level (Table S 4.1).

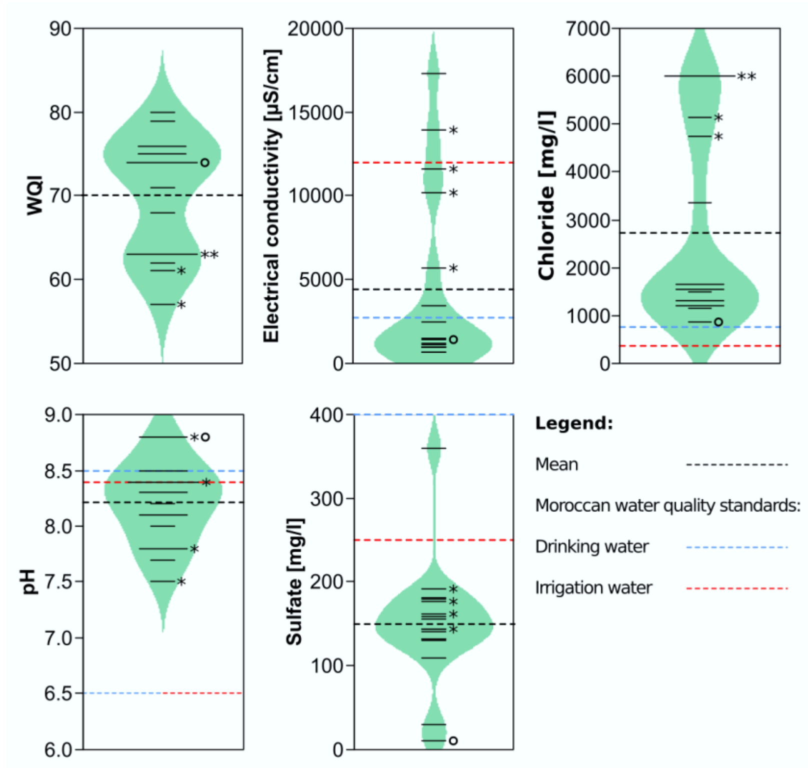

Figure 5.3. Beanplots (Kampastra, 2008) showing the distribution of values for the WQI and the parameters where water quality standards were exceeded (electrical conductivity, chloride, pH, and sulfate). The circle indicates the site located in the Middle Draa; asterisks indicate the four sites in the Lower Draa, remaining sites are in the Upper Draa.

4.5.2. Biological quality

4.5.2.1. Macroinvertebrates

Sites located in the Middle and Lower Drâa showed low values for most metrics, as reflected in the BQI (Figure 4.4). Only for %EPT the value of the Middle Drâa is located above the mean.

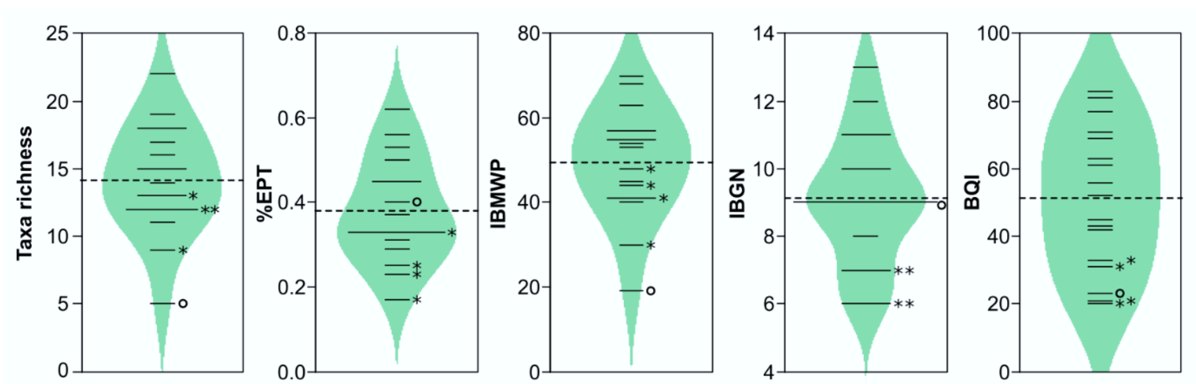

Figure 5.4. Beanplots showing the distribution of values for the biological quality metrics and the BQI. The dashed line shows the mean. The circle indicates the site located in the Middle Draa; asterisks indicate the four sites in the Lower Draa, remaining sites are in the Upper Draa. For abbreviations see section 2.4.

In the best-fit model as selected by the elastic net (lambda = 4.52, intercept 51.2), altitude and flow rate showed a positive, electrical conductivity negative association with the biological quality index (BQI), explaining 60 % of the variation (Table 4.2).

Table 5.2. Results of the elastic net for the biological quality index (BQI) and human health index (HSI) showing parameter estimates of all included variables, lambda, and coefficient of determination (R^2).

Parameter	**Estimate BQI**	**Estimate HSI**
Intercept	51.2	53.4
Altitude	6.6	4.1
Flow rate	6.4	0
Water temperature	0	-0.8
pH	0	-5.2
Electrical Conductivity	-0.04	-1.8
Dissolved oxygen	0	0
Nitrate	0	3.5
Orthophosphate	0	0
lambda	4.52	5.3
R^2	0.6	0.75

4.5.3. Human well-being

Responses were similar across gender and occupation. Higher age was associated with a lower rating of drinking water quality, lower health status, and lower satisfaction, however, showing very low effect sizes for drinking water quality and satisfaction (Table S 4.3).

4.5.3.1. Water and crop quality

Water quality for drinking and irrigation as well as crop quality were rated generally good in the Upper Drâa (Figure 4.5). In the Middle Draa, people were rating irrigation water and crop quality as less good than in the Upper Draa. People using treated groundwater through taps rated drinking water quality 48 to 60 percent higher in the Middle and Lower Drâa respectively compared to untreated groundwater, whereas the quality of truck-delivered water was rated lower than untreated groundwater. There were no differences in the rating of irrigation water and crop quality between the use of groundwater and water from rivers and springs in the Upper and the Middle Drâa (Table S 4.4). Clearer differences between the ratings were observed in the two villages of the Lower Drâa (Table S 4.4).

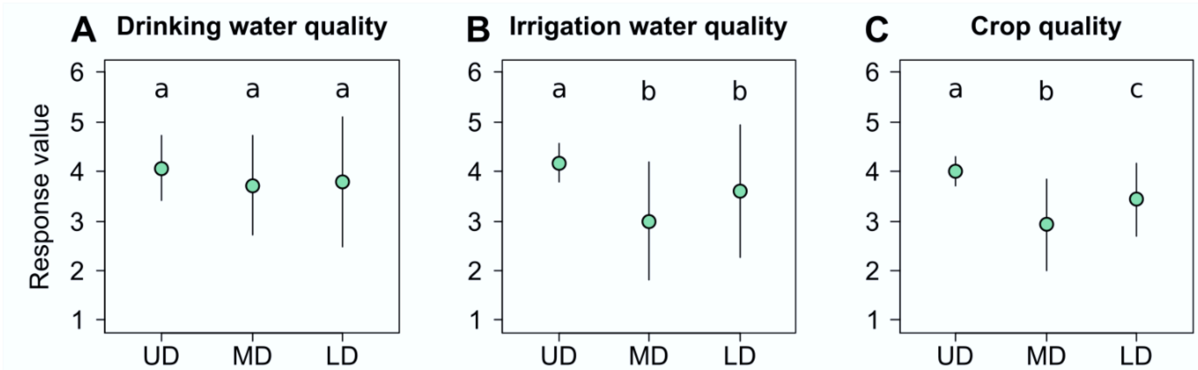

Figure 5.5. Response values from 1 (very bad) to 6 (excellent; Table S 4.2) with SD for the Upper (UD, n = 101), Middle (MD, n = 56), and Lower Drâa (LD, n = 24) for drinking water quality (A), irrigation water quality (B) and crop quality (C). The mean values of sub-basins not sharing a lower-case letter are significantly different ($p < 0.05$).

Water was perceived by people to be sometimes salty in 27 % of the sites of the Upper Drâa, whereas the others did not perceive water to be salty. In the Middle and Lower Draa, 59 and 50 %, respectively, perceived water to be salty, with in total of 39 and 29 %, respectively, stating that they experience it to be salty often.

4.5.3.2. Health status

No differences were found in how people perceived their health status throughout the Drâa River basin, with a total mean of 7.3 (SD = 1.4) on a scale from 1-10 (Table S 4.4). Of the respondents, 8, 18, and 54 % in the Upper, Middle, and Lower Draa, respectively, indicated that the quality of water influences the health of people, of which 75, 89, and 46 % said that this effect is predominantly bad for the health status. Only four percent of people in the Upper Draa, but 25 and 54 % in the Middle and Lower Draa, respectively, reported physical diseases that they attributed to water salinity. While in the Upper Draa, physical diseases were only experienced sometimes, 14 and 54 % of those who experienced it in the Middle and Lower Drâa stated that they occur often. 34%, 89%, and 38% reported emotional distress due to water salinity and/or scarcity in the Upper, Middle, and Lower Draa, respectively.

4.5.3.3. Human satisfaction

Except for satisfaction with health care, with which respondents were generally unsatisfied, all other aspects of satisfaction followed a similar pattern of between-subbasin differences (Figure 4.6, Table S 4.5), with differences being less strong in overall life satisfaction. The Upper Drâa had the highest mean response values for people being predominantly satisfied, significantly higher compared to the Middle Drâa where they are predominantly unsatisfied to very unsatisfied. Mean response values of the Lower Drâa were in between the other subbasins, however showing a very high variance caused by highly different response values between the two survey sites of Akka and Mrimima. This is also reflected in the HSI values (Figure 4.7), with the people in the Upper Drâa showing generally higher HSI values, except for the high variance in the Lower Drâa (Figure S 4.1).

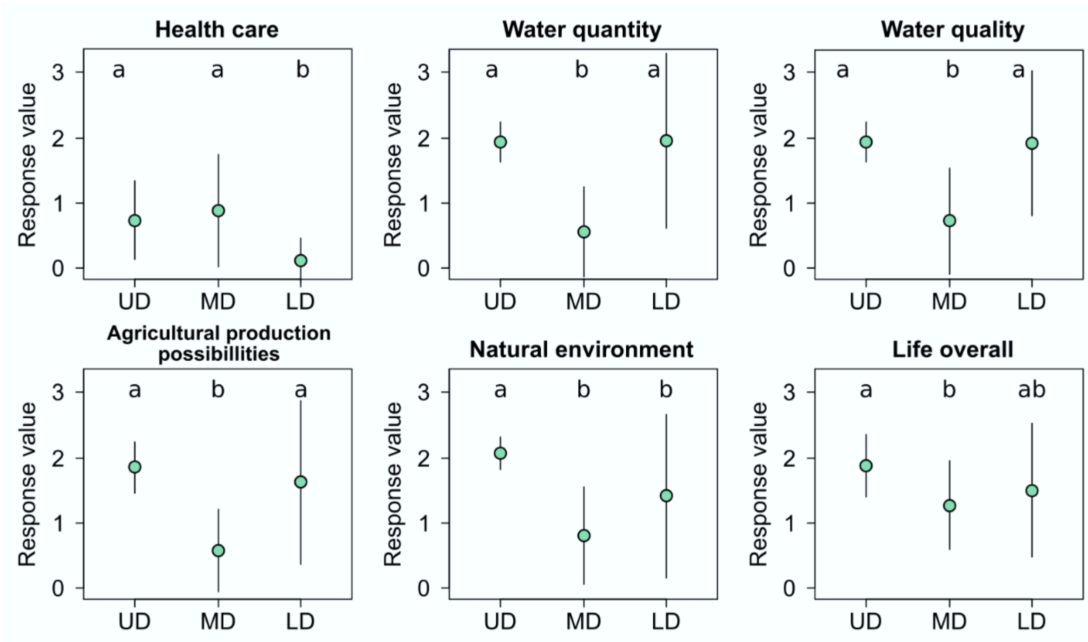

Figure 5.6. Response values from 0 (very unsatisfied) to 3 (very satisfied; Table S.2) with SD for the Upper (UD, n = 101), Middle (MD, n = 56), and Lower Drâa (LD, n = 24) for satisfaction with different aspects. The mean values of sub-basins not sharing a lower-case letter are significantly different ($p < 0.05$).

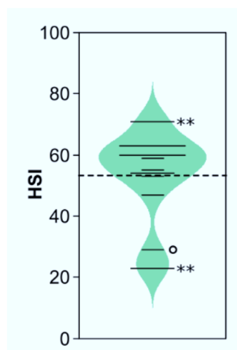

Figure 5.7. Beanplot showing the distribution of values for the mean HSI (Human Satisfaction Index) per site. The dashed line shows the mean overall. The circle indicates the site located in the Middle Draa; asterisks indicate the four sites in the Lower Draa, remaining sites are in the Upper Draa. Compare Figure S 4.1 for individual respondent HSI values.

In the best-fit model as selected by the elastic net (lambda = 5.3, intercept 53.4), altitude and nitrate showed a positive, water temperature, pH, and electrical conductivity a negative association with the human satisfaction index (HSI), explaining 75 % of the variation (Table 4.2).

4.5.4. Comparison of WQI, BQI and HSI

The WQI was correlated with the BQI (Pearson's $r(15) = 0.6$, $p = 0.01$) in the 17 ecological sites (Figure 4.8). In the 11 survey sites, the HSI was only weakly, i.e. not significantly, correlated with BQI (Pearson's $r(9) = 0.5$, $p = 0.11$), and not with WQI (Pearson's $r(9) = 0.25$, $p = 0.45$). Values for the Upper Drâa were generally high compared to the other sites (Figure 4.8). The individual components of satisfaction included (mean values per site) in the HSI were not significantly correlated to the WQI and BQI, either, except for satisfaction with the environment that correlated with BQI (Table S 4.5)

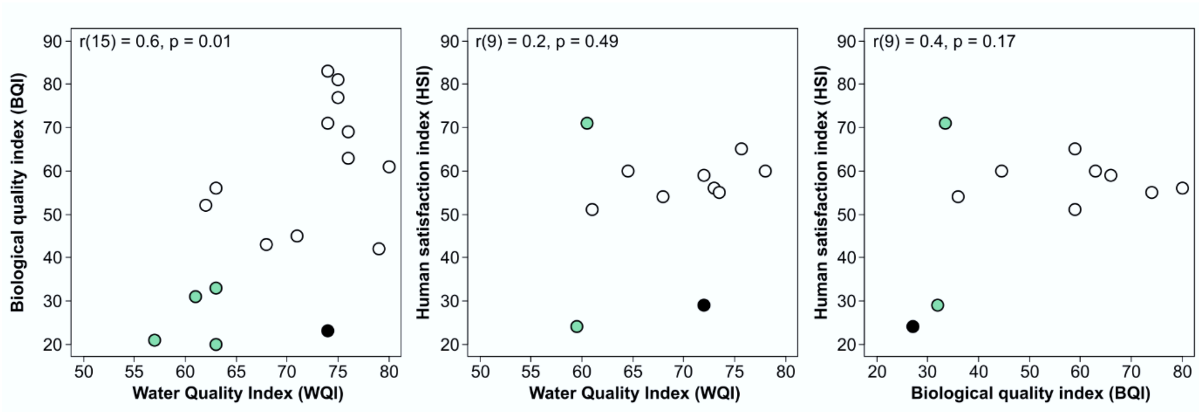

Figure 5.8. Scatter plots showing correlations of river water quality index (WQI), biological quality index (BQI, and human satisfaction index (HSI). Green points = Upper Drâa, black points = Middle Draa, white points = Lower Draa.

4.6. Discussion

4.6.1. Water quality and quantity

We found that the water quality index of rivers in the Drâa River basin is mainly determined by salinity. Sites with higher electrical conductivity and higher chloride concentrations scored lower in water quality index values and concentrations often exceeded maximum admissible values for human consumption (Royaume du Maroc, 2006) and irrigation (SEEE, 2007). This is following our first hypothesis. Low values of other parameters like phosphate indicate low pollution of the river water. This may be explained by fertilizers being rarely used in the mainly traditional farming that is conducted in the Drâa River basin (Ou-Zine et al., 2021). This result should be interpreted with caution as other components of water quality that may indicate pollution such as BOD5, DOC, total phosphorus, and fecal coliforms, were not determined. With further primary salinization due to increasing aridity (Beck et al., 2018; Williams, 1999) and ongoing secondary salinization, especially in the Middle and Lower Drâa area (Warner et al., 2013), river water quality is likely to further degrade in the future.

The rating of the quality of water resources by respondents was largely consistent with the measured river water quality in terms of salinity, with most people in the Lower Drâa region reporting poorer water quality and perceiving the water to be salty. Besides river water, groundwater can be affected by high and increasing salinity (Warner et al., 2013), limiting access to usable drinking and irrigation water. However, the treatment of drinking water (e.g., ONEE tap water, mainly pumped from aquifers to water towers where it is treated) could explain the little differences in perceived drinking water quality in the three sub-basins. Perceived irrigation water quality was lower in the more saline and dry Middle and Lower Draa. Salinity levels well below the maximum admissible values for irrigation water of 12 mS/cm (SEEE, 2007) can already drastically reduce the growth and yield of salt-tolerant plants such as date palms (Tripler et al., 2011). While river water is used for irrigation in the Upper Draa, groundwater is mainly used in the Middle and Lower Draa, because river water is only available after dam releases or rain events or is too saline. Wells are deepened, or new ones are constructed (Berger et al., 2021), leading to increasing over-exploitation of aquifers (Hssaisoune et al., 2020). The increased water salinity and scarcity, among other factors (Dessu et al., 2014), may explain the dissatisfaction with water quality and quantity in the Middle and Lower Draa, as we saw associations of human satisfaction with altitude, electrical conductivity, and water temperature, though not with flow rate. However, as water quality was only investigated at one site in the Middle Drâa and the other sites were dry during the sampling period, the transfer of this result to the entire sub-basin should be treated with caution. With an increasingly dry climate (Beck et al., 2018; Tramblay et al., 2018), and intensive cultivation of water-demanding crops such as watermelons (Hssaisoune et al., 2020; Karmaoui et al., 2016), river ecosystem health and human well-being may be further compromised in the coming decades (Karmaoui et al., 2019).

4.6.2. Biological quality

The biological quality of rivers in the Drâa River basin was positively correlated with river water quality, with a general decline from up to downstream. Additionally, biological quality was, following our second hypothesis, negatively associated with high electrical conductivity and low flow rate. High salinity limits the survival of non-adapted species (Kaczmarek et al., 2021), with only saline specialist or generalist species surviving (Arribas et al., 2019; Samraoui et al., 2021). Consequently, sensitive taxa such as various ephemeropterans, plecopterans, and trichopterans (EPT) were absent in the saline sites of the Lower Draa, which is reflected in the IBGN (Archaimbault & Dumont, 2010). Low flow rate and the periodical drying of rivers further reduce macroinvertebrate richness (Beauchard et al., 2003), as many species are adapted to high flow velocities (Samraoui et al., 2021) and cannot tolerate stress caused by low flow or standing waters, cannot withstand desiccation, or are unable to complete their life cycles during shorter wet periods of the river (Stubbington et al., 2017). The Middle Drâa is separated from the Upper Drâa by the El Mansour Eddahbi dam. Because the Middle Drâa only leads to flowing water after dam releases or heavy rain events, adaptations to short reproductive cycles and stagnant flow are required (Kaczmarek et al., 2021; Samraoui et al., 2021). An increase in salinity and aridity in the coming decades (Hssaisoune et al., 2020, Terink et al., 2013) and the construction of dams (Zarfl et al., 2015) may lead to the loss of salt-sensitive or non-adapted species (Kaczmarek et al., 2021), compromising biological quality of rivers.

As a specific multimetric macroinvertebrate index for assessing river water quality, biological quality, or ecosystem health is lacking in most of Africa (Edegbene et al., 2019), we decided to combine several metrics. Overall, the biological quality index had the lowest values for the high salinity sites in the Lower Drâa and the stagnant pool in the Middle Draa, suggesting that it is suitable for indicating generally poor conditions for human use in saline and arid sites. This is also reflected in the low scores for these sites in the IBMWP and IBGN, which were created to assess biological water quality using indicator organisms (Jáimez-Cuéllar et al., 2002; Archaimbault & Dumont, 2010). While measured river water quality in the site of the Middle Drâa was better than in the Lower Draa, as also reflected in the IBGN, intermittency, and stagnant flow resulted in poorer biological quality values compared to the saline sites. Overall, the IBMWP and the IBGN seemed to be useful in detecting poor biological water quality in saline and low flow sites of the Draa River basin compared to the other sites of the Draa, though they do not account for the reference state in terms of the natural state of saline streams and their communities. Although we found a correlation between river water and biological quality, we did not achieve a differentiation between the impact of primary and secondary salinization. Naturally saline streams may be unsuitable for human use and score low in commonly used multimetric macroinvertebrate indices, still, they can harbor unique communities. This indicates the need for specific indices and indicator organisms for saline and intermittent streams (Arias-Real et al., 2022), especially to detect anthropogenic impacts in naturally stressed ecosystems (Gutiérrez-Cánovas et al., 2019). However, more research is needed to define indicator organisms for yet less studied regions (Gutiérrez-Cánovas et al., 2019) and to further develop indices to monitor climate change and anthropogenic impacts on naturally saline streams (Gutiérrez-Cánovas et al., 2008).

Besides macroinvertebrates, other organisms such as riparian plant species (Mostakim et al., 2020) and vertebrates (Riesco et al., 2020) are affected by increasing primary and secondary salinization, as well as increasing aridity in the Drâa River basin. A loss of species and a change of assemblage composition can disrupt ecosystem functioning (Lecerf & Richardson, 2010) and reduce ecosystem resilience to disturbance (Peterson et al., 1998). Conservation efforts should, however, not only focus on perennial freshwater rivers (Cañedo-Argüelles et al., 2016), but also take naturally saline and intermittent rivers and their adapted communities into account (Benamar et al., 2021; Velasco et al., 2006), as these species may have the potential to colonize anthropogenically salinized and intermittent rivers (Kefford et al., 2016). When important species are lost, other species, like invasive alien species, may proliferate (Clavero et al., 2015), potentially reducing human well-being (Jones, 2017) by for example an increase in species that transmit diseases to humans, such as mosquitoes (Ramasamy & Suredran, 2012) and pathogenic microorganisms (Keesing & Ostfeld, 2021). The aim to reduce the impact of secondary salinization on the river ecosystem and thereby safeguard human well-being may be compromised by future efforts to provide freshwater resources for drinking and irrigation water, like the cross-basin water transfers to other regions (El Moçayd, et al., 2020).

Asked about satisfaction with the natural environment, respondents were particularly dissatisfied along the mostly dry Middle Drâa River. Other studies showed that healthy environments have a positive impact on satisfaction (Hartig et al., 2014). However, we found no correlation between human satisfaction overall and biological quality, which contradicts our third hypothesis. As the Middle Drâa was mostly dry during the study period, we could not study water and biological quality in this area, where satisfaction was low. Data from more sites along the Middle Drâa might have resulted in clearer trends. However, the missing differentiation between naturally saline and anthropogenically salinized rivers in biological quality indices could have led to higher biological quality in natural high saline sites. Nevertheless, we found high levels of satisfaction mainly in the Upper Drâa area where biological quality was typically good. While respondents in Akka in the Lower Drâa showed the highest satisfaction although living in an area showing low biological quality, we expect that this is related to their situation of high-water availability with relatively low salinity levels for the Lower Drâa region compared to their direct neighbors.

To maintain biological quality of rivers, measures are needed to limit increasing water demand and salinity. This can be achieved through water strategies, including improving irrigation efficiency (Hssaisoune et al., 2020; Jeddi et al., 2021) and reducing agricultural areas (Johannsen et al., 2016), especially for water-demanding crops such as watermelon (Karmaoui et al., 2016). Further intensive use of water resources would limit ecosystem functioning, leading to a loss of ecosystem services (Jakubínský et al., 2021) and thus may compromise river ecosystem health and human well-being.

4.6.3. Human health

Respondents reported generally good health conditions while being unsatisfied with health care. Although differences in health status were low between sites in the whole basin and a clear association with biological quality was lacking, every tenth person reported negative effects from water, such as fecal-oral diseases and tooth discoloration. However, these effects are not necessarily caused by river water directly, as the bacteriological quality of water could be reduced between source and point-of-use (e.g., during central storage in water towers or storage in households; Wright et al., 2004). About half of the respondents from the Lower Drâa reported physical diseases attributed to water salinity, (e.g., kidney problems). Similarly, it was stated that salinity in drinking water might have a connection with kidney diseases like kidney stones and Rheumatism (SRTT, 2011).

Besides physical diseases, nine out of ten respondents in the Middle Drâa reported emotional distress caused by both water salinity and scarcity, whereas it was reported by about a third of respondents in the Upper and Lower Draa. Previous studies suggested that a low predictability of supply is a contributor to emotional distress (Stevenson et al., 2012, Wutich et al., 2016, Wutich & Ragsdale, 2008,). Several factors may explain the low predictability: natural factors include the decreased precipitation in the area, whereas the management-related ones mainly include flow regulation through the dam which is contributing to the intermittent characteristic of the Middle Draa. Other contributors to emotional distress could be caused by witnessing wetland degradation or destruction over the years (Larsen, 2012).

4.6.4. Human well-being

Aspects of human well-being covered in this analysis, namely water and crop quality, health status, and satisfaction (which includes satisfaction with health care, water quality and quantity, agriculture possibilities, environment, and life overall in the area) are partly provided by the river ecosystem in the three Drâa sub-basins. However, we did not find a significant correlation of human satisfaction with the water and biological quality indices, with only satisfaction with the conditions of the natural environment showing a positive correlation with the biological quality. River naturalness positively affects health and well-being among individuals, while a disconnection from nature may have detrimental effects on human satisfaction, as well as contributing to an unhealthy environment (Kaplan et al., 1989, Kaplan 2001; Nasar 2000; White et al., 2010). Similarly, our results indicate that respondents in the Upper Drâa were predominantly satisfied with the natural environment, in contrast to the Middle Drâa where respondents expressed missing the riverscape for years. While we found a correlation of satisfaction with the conditions of the natural environment and aspects regarding water quantity and quality as well as agriculture, satisfaction with health care showed no correlation with those aspects. Other important intangible aspects of human well-being require further research for the Drâa and other areas (e.g., spirituality, identity, cognition). When considered, these may provide stronger associations between the state of the ecosystem and human satisfaction and well-being. Our knowledge could be advanced by studies with a more comprehensive perspective that assesses how the different constituents of well-being benefit from nature.

4.7. Conclusion

Our findings indicate that high salinity levels and low water flow are reducing the water and biological quality of rivers in the Drâa River basin. However, as current biological indices fail to discriminate between naturally saline and anthropogenically salinized rivers and, thus, potentially assign a too low biological quality to naturally saline rivers, specific indices would be required for a better assessment of their status. Our study suggests direct and indirect relationships between the state of the river ecosystem and human well-being, such as saline river water directly causing human emotional distress and decreasing satisfaction. However, several correlations were much weaker than hypothesized or non-existent. We suspect that the relationship can be masked by additional factors such as the cultural background specific local needs or water usage so that more comprehensive surveys with more detailed and open interview questions and complex statistical tools may be required to find those associations. In addition, a larger sample size would increase the capacity to detect relationships. Targeting countries of the Global South is crucial, as these are particularly vulnerable to the effects of climate change on their nature, economy, and society, in particular on water supply for nature and humans. In this context, to improve human well-being, policies, and action plans should consider the interdependence between ecosystems and their inhabitants.

Chapter 5

What water governance challenges and opportunities arise in arid regions? Lessons from the Middle Drâa Valley, Morocco

Silva-Novoa Sanchez Luis Miguel [a], Imane Mahjoubi [a], Oliver Frör [a], Lisa Bossenbroek [a], Janpeter Schilling [a, b, c] and Elisabeth Berger [a]

[a] RPTU - Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau - Institute for Environmental Sciences, Germany.

[b] Department of Police and Security Management - Berlin School of Economics and Law, Berlin, Germany.

[c] Peace Academy Rhineland-Palatinate, RPTU, Landau, Germany.

Adapted from the manuscript submitted on March 19th, 2024.

5.1. Abstract

The strain on global aquifers, particularly in arid regions, is increasing, emphasizing the strategic importance of these resources amid escalating resource degradation. Scholars increasingly recognize the contextual specificity of water governance issues, challenging the prescription of universal solutions. In this context, whether and how groundwater degradation could be reversed remains an urgent question to address, directing attention to governance frameworks. This paper investigates three cases of groundwater governance in Morocco's Middle Drâa Valley (Faija, Fezouata, and M'hamid), to provide empirical insights into governance challenges and opportunities in this arid region. Guided by governance modes, the Social-Ecological System Framework, and incentive structure analysis, we analyzed 76 semi-structured interviews, 30 structured interviews, and 2 focus group discussions. We found that water users face diverse governance challenges that are influenced by each social-ecological system's unique features. Hierarchical governance, self-governance, and hybrid models emerge as different governance modes. Institutional diversity reflects variations in each area's social-ecological system, presenting challenges in aligning governance efforts between self-governance institutions and governmental organizations. Government-proposed aquifer contracts may provide a framework to address this issue by promoting a unified governance system for self-governance and governmental organizations in each aquifer. However, our analysis shows that significant adjustments are needed to enhance resource user involvement in decision-making and ensure rule adherence.

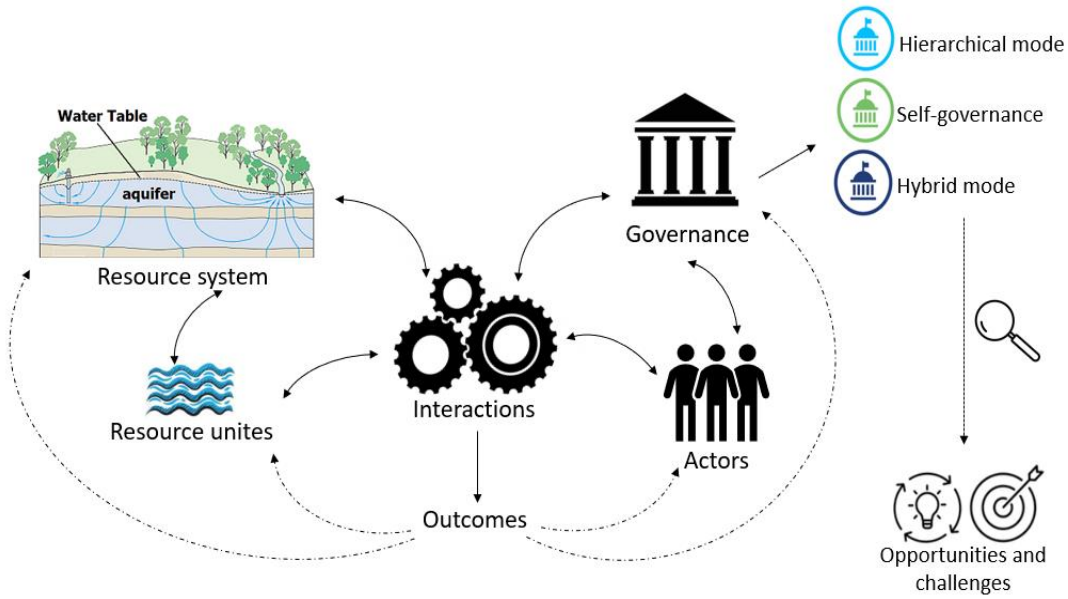

Figure 5.1. Graphical Abstract for Chapter 5.

5.2. Introduction

The strain on global aquifers, particularly in arid and semi-arid regions, is intensifying (Fienen & Arshad, 2016; Kuper et al, 2016; Kuper et al., 2017; Lezzaik et. al, 2018; Hssaisoune et al., 2020). This occurs along with a growing strategic importance of groundwater for drinking water production, agriculture, and industry, all of which contribute to socio-economic development. Consequently, in the last decade, there has been increased attention to how to design governance systems that allow resource sustainability, equitable allocation, and socioeconomic development (Pahl-Wolst, 2015; Pahl-Wolst, 2019).

The management of groundwater resources poses a significant challenge due to their open-access nature, making them susceptible to overexploitation (Holt et al., 2021). As common Pool Resources (CPR), aquifers exhibit conditions that foster individual appropriation for users' immediate benefit, often at the detriment of communal interests, thereby promoting unsustainable resource utilization and inciting conflicts (Baldwin et al., 2018). CPR theory suggests the necessity of collective action among users to create rules and norms to address this behavior and promote sustainable governance systems (Ostrom, 2009; Poteete et al., 2010; Baldwin et al., 2018). However, coordinating this action among diverse users poses multilevel and multiscale coordination challenges that exceed the capacities of locally focused water user organizations. The question of how to effectively structure water governance processes, integrating the efforts of local user organizations with governmental entities across various levels and scales, remains unresolved (Baldwin et al., 2018; Molle & Closas, 2020; Slough et al., 2021; Munoz-Arriola et al., 2021). As Molle & Closas (2020) pointed out, the question of whether and how the trend of groundwater degradation could be reversed interrogates governance frameworks and remains a question that is urgent to address.

The OECD's assertion that "water crises are often primarily governance crises" (OECD, 2011) underscores the growing importance of water governance. However, contemporary policymakers and water practitioners tend to adopt a narrow view of governance, conflating it with normative water management approaches (Closas & Villholth, 2019). This conflation has drawn criticism for oversimplifying water governance issues and proposing solutions that fail to address the complex socio-environmental challenges comprehensively. Managerial solutions often stem from inadequate groundwater knowledge, resulting in interventions that overlook fundamental resource limitations and context-specific groundwater challenges (Ingram, 2011; Closas & Villholth, 2019; Zwarteveen et al., 2021). Furthermore, this managerial approach fails to address power dynamics and inequities in water benefit distribution, thereby overlooking the socio-political dimensions of governance and offering incomplete solutions (Castro, 2007; Boelens & Vos, 2012; Zwarteveen et al., 2017; Closas & Villholth, 2019). Critics argue that groundwater governance cannot adhere to a prescribed, linear process of policy decision-making and management rule implementation (Molle, 2008; Mehta et al., 2018; Woodhouse and Muller, 2017; Closas & Villholth, 2019).

An alternative perspective on water governance challenges the notion that governance represents an idealized form of sustainable resource management. Instead, it views governance as an ongoing process embedded within society, shaped by various stakeholders with divergent agendas, thus constituting a specific governance reality (Closas & Villholth, 2019). Governance, according to Birkenholtz (2014), arises from interactions among users, communities, and the state, rather than being a controlled process. As articulated by Zwarteveen et al. (2017), "Water governance at heart is about political choices regarding water flow, the norms, rules, and laws guiding these choices, who has the authority to decide, and the societal future these choices endorse" (Zwarteveen et al., 2017: 8).

In this study, we adopt the latter conceptualization of water governance. Our objective is to examine the development and operation of institutional arrangements for groundwater governance in the Middle Drâa Valley (MDV) of Morocco, aiming to offer empirical insights into the specific groundwater governance challenges in this arid region. To achieve this, we analyze three aquifers: Faija, Fezouata, and M'hamid, addressing the following research questions: 1) What are the characteristics of groundwater governance in the MDV? 2) How is groundwater governance influenced by the contextual specificities of the social-ecological system? and 3) What factors impact rule compliance within the identified groundwater governance systems? Our analysis is guided by governance modes (Kooiman, 2000, 2003), the Social-Ecological System Framework (SESF) (McGinnis & Ostrom, 2014), and an incentive structure analysis approach (Kerr et al., 2012; Wight et al., 2021).

The concept of governance modes encompasses ideal typologies aimed at describing various patterns in which governance processes are structured. Different typologies focus on distinct aspects or dimensions of governance. In this paper, we utilize a typology that highlights the roles of governmental and non-governmental actors in creating, monitoring, and sanctioning governance institutions. This typology delineates between "hierarchical governance," "self-governance," and "co-governance" (Kooiman, 2000, 2003). Hierarchical governance, also known as "command and control" (Varady et al., 2016) or "bureaucratic governance" (Pahl-Wostl, 2019), entails top-down governmental control with regulatory processes primarily based on formal rules and sanction mechanisms. Hierarchical governance often involves permits, quotas, and extraction restrictions. In contrast, self-governance represents a departure from top-down governmental control, where actors autonomously govern themselves, independent of government oversight (Symes, 2006). An example is community-based management of water resources, where local users establish rules for resource allocation, infrastructure use, and maintenance, as well as monitoring and rule enforcement. Co-governance, also known as interactive or collaborative governance (Kooiman, 2016; Pahl-Wostl, 2019; Molle & Closas, 2020), occurs when public and private actors coordinate and communicate to address issues without a central governing authority. In such cases, resource users, whether community-based or not, have decision-making power and share responsibilities with the government (Pahl-Wostl, 2019; Molle & Closas, 2020).

While recognizing the inherent limitations of typologies, we acknowledge that our aim is not to capture every aspect of governance comprehensively. We also understand that empirical data collected in the field may not neatly fit predefined categories. Our analysis aims to shed light on how governance processes align with or diverge from these typologies, and the underlying reasons for such patterns. Therefore, our goal is to maintain simplicity while using this typology as a starting point for a more nuanced examination of the roles of governmental and non-governmental actors in governance processes, particularly in formulating, monitoring, and enforcing resource use rules. We chose to focus on the aquifers of Faija, Fezouata, and M'hamid due to their distinct social-ecological characteristics and the diverse groundwater governance responses they exhibit to these conditions.

We employ the SESF to characterize the SESs of the three groundwater governance cases (See section 3.1). Our aim is not to encompass the full array of interactions within each SES. Instead, we utilize the SESF to pinpoint relevant variables that elucidate the groundwater institutional arrangements and as a common language for communication with the scientific community. To understand the factors influencing compliance with groundwater regulations, we integrate the SESF with an incentive structure analysis approach. This approach operates under the premise that individuals and organizations respond to incentives, with their behavior shaped by associated costs and benefits (RB Howarth et al., 2000; Bolton and Ockenfels, 2000; Gneezy et al., 2011). Combining these approaches is relatively uncommon, and thus, another objective of this paper is to evaluate the utility of the SESF in understanding the specific challenges within each SES identified in the MDV, along with the added value of integrating an incentive analysis. We contend that employing incentive analysis reveals the complexities of rule compliance within each case. We address this question in the discussion section, highlighting the advantages and limitations of each analytical framework and how they complement each other.

The paper is organized as follows: section 5.3 gives an overview of the study area and Section 5.4 explains the methods used in the analysis. Section 5.5 contains the results, which are presented in three sub-sections, each one devoted to each case. In section 4.6 we critically discuss our findings. Finally, we present our conclusions in section 4.7.

5.3. Study area

The Middle Drâa Valley (MDV) is located in the province of Zagora in the southeastern part of Morocco, in the north of the Sahara Desert (Figure 5.2). This region is characterized by an arid to hyper-arid climate (Klose, 2016) with annual average precipitation of 70 mm (Moumane et al., 2021), and average potential evaporation of up to 3000 mm (Karmaoui et al., 2015; Schulz, 2006). The valley contains six oases, each oasis as an aggregation of small plots in which local inhabitants cultivate diverse crops on different levels. Date palm and fruit trees form the garden canopy and serve as cash crops and create a microclimate for lower-level crops such as alfalfa for livestock feed and self-consumption crops like wheat, corn, and vegetables.

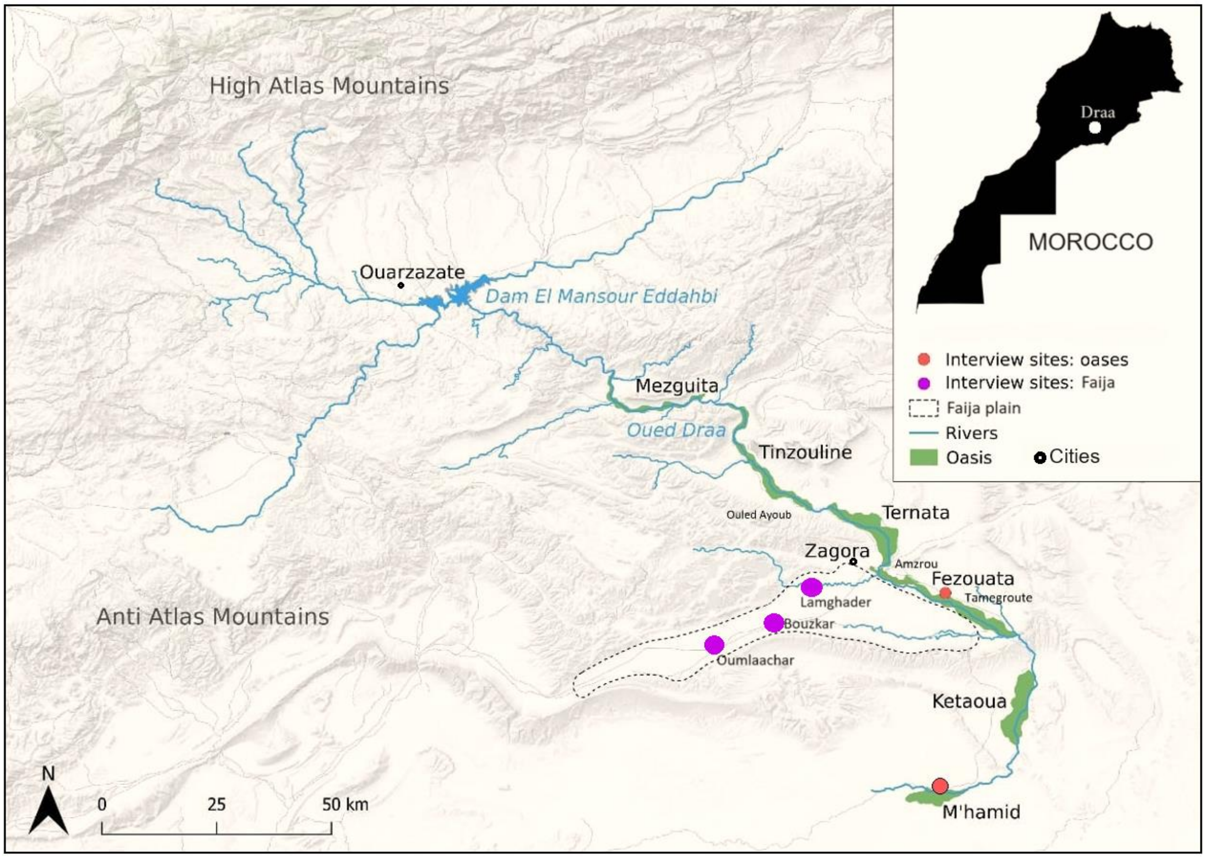

Figure 5.2. Map showing the case studies' locations and interview sites.

The MDV historically relied on agriculture as the main occupation and source of income for locals. Water scarcity and salinity have driven migration from the area (Ait Hamza, 2010; Rademacher-Schulz, 2014). Since the mid-1970s, frequent and prolonged droughts have Increased dependence on groundwater, facilitated by affordable pumps, well infrastructure, and solar panels, leading to declining water tables (Kuper et al., 2016; Houdret & Heinz, 2022; Hssaisoune et al., 2020; ABH, 2022). The El Mansour Eddahbi Dam, built in 1972, aimed to secure water for Ouarzazate, and has contributed to reducing aquifer recharge rates in the valley (Ait Hamza, 2010). The Green Morocco Plan (2008–2020) promoted agriculture development with subsidies for drip irrigation systems. In the MDV, this plan has contributed to expanding groundwater-based farming in the lands surrounding the traditional oases, increasing pressure on the MDV aquifers.

As stated in the introduction, our study centers on the Faija Plain, Fezouata, and M’hamid aquifers, which are situated within the same river basin. Despite their shared geographical context, we chose to treat them as distinct case studies due to their representation of varying governance modes—both self and hierarchical—discussed earlier. Additionally, they exhibit diverse social-ecological characteristics and possess different institutional frameworks for groundwater management, each catering to user communities with unique attributes. This diversity allows us to explore how the intricacies of each SES are intertwined with the constraints and hurdles faced by these groundwater institutional arrangements.

5.4. Methods

5.4.1. The Social-Ecological System Framework

The SESF addresses social-ecological systems as an aggregation of subsystems that "are relatively separable but interact to produce outcomes at the SES level, which in turn feedback to affect these subsystems and their components, as well as other larger or smaller SESs" (Ostrom, 2009: 419). We treat each of our aquifer cases (Faija, Fezouata, M'hamid) as SESs. The SESF focuses on the analysis of four main components of the SES: Resource System (RS), Governance System (GS), Resource Units (RU), and Actors (A). According to McGinnis and Ostrom (2014), the framework was designed to be applied to relatively well-defined domains of common-pool resource management situations in which resource users extract Resource Units (in our case studies groundwater) from Resource Systems. The behavior of the actors in the SES is determined by the biophysical characteristics and dynamics of the Resource System, by the rules and procedures determined by the Governance System in place, and by broader social-political-economic settings as well as the related ecosystems.

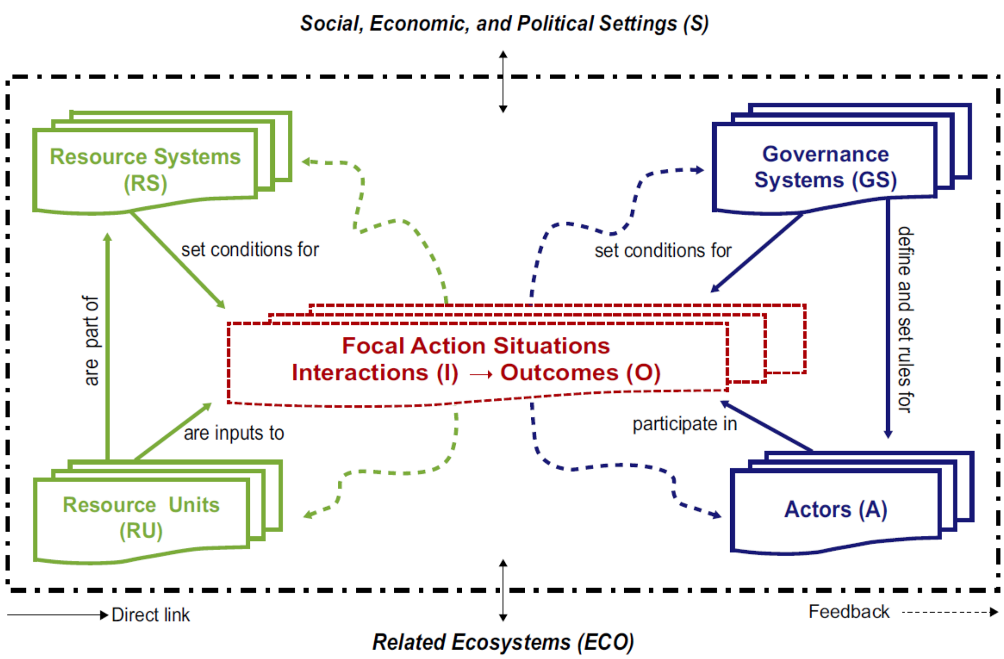

Figure 5.3. The Social-Ecological System Framework (*McGinnis and Ostrom, 2014).*

Resource units, resource systems, actors, and governance systems are the highest-tier variables that contain multiple variables at the second tier (Figure 5.3). Focal Action Situations refer to processes by which the inputs of the different components of the SES are transformed by the actions of multiple actors into outcomes. In our case studies (Faija, Fezouata, M'hamid), the focal action situation refers to groundwater use and the governance challenges linked to groundwater distribution between users and resource degradation prevention. The dotted-and-dashed line that surrounds the interior elements of figure 5.3 indicates that the SES analyzed can be considered as a logical whole, but that exogenous influences from related ecological systems or social-economic-political settings can affect any component of the SES. These exogenous influences might emerge from the dynamic operation of processes at larger or smaller scales than that of the focal SES (McGinnis and Ostrom, 2014: 4).

The SESF assumes that actors make choices among available options in light of information about the likely actions of other actors and the benefits and costs of potential outcomes. In this way, the social and ecological outcomes in each SES are conceptualized as consequences of actors' actions in interaction with the Resource System, the Governance System, and the broader social-political-economic settings. The outcomes referred to in the Common Pool Resources (CPR) and Social-Ecological System (SES) literature are typically environmental outcomes (in our case impacts in groundwater resources conditions), social outcomes in connection to resource access, and outcomes in terms of governance institutions performance (Figure 5.3 and appendix 5.1).

5.4.2. The Incentives Adequacy Approach

In the natural resources management sector, "incentives" refer to mechanisms designed to steer the behavior of individuals and communities toward more responsible use of resources and compliance with regulations, to achieve in this way public policy goals (Kerr et al., 2012). We compiled and updated a standardized incentives scheme (see Appendix 2) from Kerr et al. (2012), Rapoport and Wing, (2001), Travers et al. (2011), and Vatn (2009). This scheme encompasses two broad categories: "financial incentives'' (such as tax incentives, tradable environmental permits, penalties, subsidies, rebates, and other monetary advantages) and "non-financial incentives'' (including information dissemination, collaborative monitoring, performance-driven agreements, technical support, and social motivation) (Minehart and Neeman, 2004; Delmas and Keller, 2005; Delmas and Montes, 2007; Nordhaus, 2015). The adequacy of incentives refers to how effective the incentives are in shaping the users' behavior in the intended way. To this purpose, we check how well the incentive design considers the particular interests, objectives, and conditions of the actors whose behavior is to be modified. The aim is to conclude incentives' ability to align individual and collective behaviors with water conservation goals (Wight et al., 2021). In the case of Fezouata and M'hamid, the incentives are already implemented and therefore, it is possible to see if they produced the intended effect on users' behavior. In the case of Faija, currently, the government is promoting an aquifer contract. The results of the new rules promoted as part of this contract have not yet materialized. In this sense, our analysis seeks to identify the elements in the contract that may hinder the success of the proposed incentives.

5.4.3. Data collection

To understand the aquifer resource systems, groundwater usage regulations, and their operational mechanisms within the areas of Faija, Fezouata, and M'hamid, it was essential to gather data on the physical characteristics of these aquifers, obtain information on the relevant actors and their socio-economic profiles as well as on the interests of the groundwater users, and the groundwater regulation used in these areas.

For all three cases, we review the statutory water law n° 19-95 (Royaume du Maroc, 1995) and n° 36-15 (Royaume du Maroc, 2016). These regulations delineate the procedures for authorizations and concessions pertaining to the public hydraulic domain. For Fezouata, where only the statutory regulations are in use, we conducted 30 questionnaires in 2022 and 25 semi-structured interviews in 2023 with farmers. For the M'hamid case, customary community rules are in use in addition to statutory regulations. To assess customary rules, we conducted 12 interviews with farmers and owners of tourism facilities in 2022. For both cases, Fezouata and M'hamid, we also relied on the 2010 Assessment Study Report of Groundwater Resources in the Drâa and Guelmim basins, commissioned by the Souss Massa Water Basin Agency.

For the Faija case, data collection was initiated by examining the aquifer contract document, an extensive 45-step action plan formulated by River Basin Agency Draa-Oued-Noun (ABH-DON) in Ouarzazate. This contract is formulated based on the water law n° 36-15. In addition, we examined study reports from ABH-DON (2020). These studies were conducted to formulate the Faija groundwater contract and contain data on the socio-economic characteristics of groundwater users and the geological and hydrological characteristics of the aquifer. These study reports include a survey database with 682 farmers. To delve into the characteristics of farmers, their resource access, the power dynamics, and the customary rules mediating access to groundwater in Faija, we conducted 25 interviews with water users in Faija in 2022. During 2023, a further 14 interviews were conducted with governmental actors and two focus group discussions with water users in Faija. These interviews and focus groups aimed to gain more understanding of the motivations and expectations to participate in the aquifer contract.

5.4.4. Data analysis

Based on the available data, we identified among the variables provided by the SESF (see Appendix 1) those variables that help us describe the particular characteristics of the SESs of Faija, Fezouata, and M'hamid. To this purpose, the software MAXQDA 2020 (VERBI Software, 2021) was used for the content analysis of both official government documents and the transcriptions of our semi-structured interviews. Following a deductive approach, we use the variables and sub-variables corresponding to Resource Systems (RS), Resource Units (RU), Governance System (GS), and Actor (A) provided by the SESF (McGinnis and Ostrom, 2014).

To better understand the groundwater regulations in place and the factors hindering compliance with these rules in the three case studies, we analyze the variable Rules-in-use (GS6) (Appendix 5.1) using an incentive adequacy analysis. In the first step, we identified rule-compliance incentives and how they are structured within the regulations, using the standardized scheme in appendix 5.2. In the second step, we assess the adequacy of the incentive structures identified. We do that by assessing the extent existing incentives align with the interests of the stakeholders and analyzing whether these incentives are sufficient to persuade users that it is more beneficial for them to comply with the rules, especially in scenarios where alignment rules and interests may be lacking. Rules and incentives were assessed within the official government documents (e.g. water laws, Faija aquifer contract) and interview transcriptions using the software MAXQDA 2020 (VERBI Software, 2021).

5.5. Results

In examining the three Social-Ecological Systems (SESs) of Faija, Fezouata, and M'hamid, we use the higher-tier variables and several of the second-tier variables suggested by McGinnis and Ostrom (2014) (Appendix 5.1). Figure 5.4 below shows the list of variables we identified and analyzed.

Here we explain some elements of the socioeconomic and political settings in which our case studies are embedded. Three policy areas influence the SESs of our case studies. 1) The water policy area, represented locally by the government institutions of ABH-DON (interested in resource conservation) and National Office of Water and Electricity (ONEE), (interest in securing drinking water production); 2) the agriculture policy area represented by the provincial and local institutions belonging to the Ministry of Agriculture, whose interest is to promote agriculture development - which contributes to increasing water demand. 3) The interior security policy area, represented by the local institutions of the Ministry of Interior Affairs, (Caïdat[3], Gendarmery, Police) responsible for enforcing statutory rules. The interest of these institutions is to keep order and peace and avoid social and political instability.

This section is divided into three subsections presenting the characterization of the SESs of our three study cases using the SES Framework proposed by McGinnis and Ostrom (2014) by using variables from figure 5.3 explained previously.

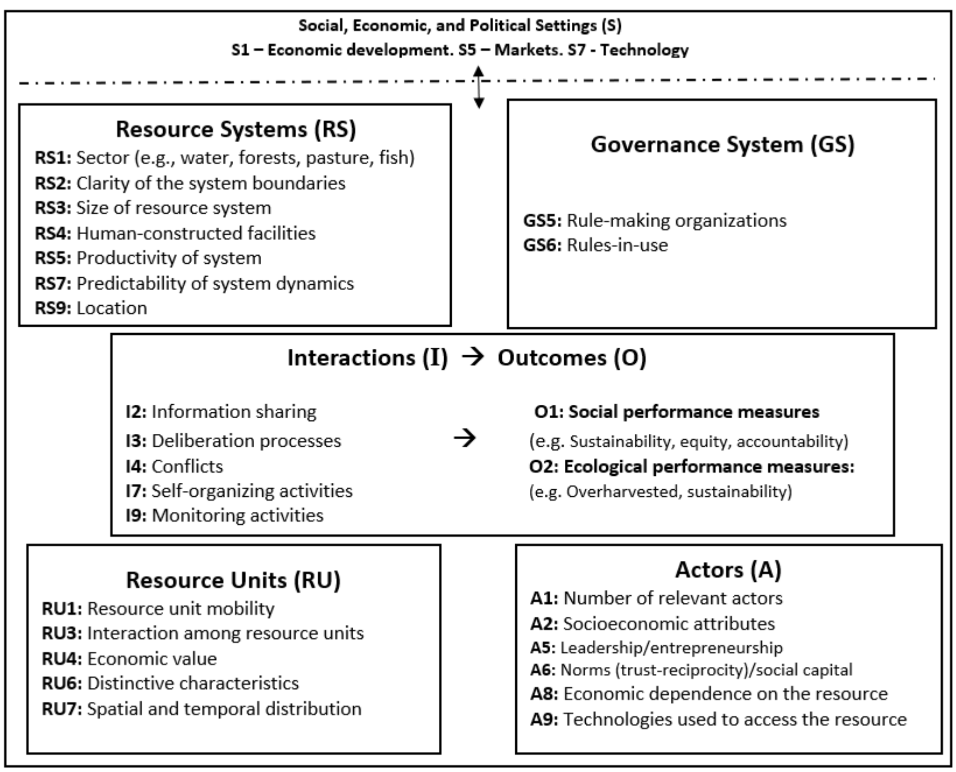

Figure 5.4. Second-tier variables used in the social-ecological system characterization (Source: Adapted from Ostrom, 2009:421).

[3] The Caïdat (or Kaïdat) is a decentralized territorial administration unit to which one or more Communes are attached. The head of the Caïdat is the Caïd, who depends on the Ministry of Interior.

5.5.1. Characterization of the Faija case

5.5.1.1. Resource System and Resource Units

Water users and government representatives define the Faija aquifer system as composed of the Faija Plain with 1,000 km2 (RS3), the mountains that border the plain, and the alluvial aquifer beneath the plain. The mountains to the north of the plain are Boukhachba and Boujniba and to the south mountain Bani. To the East, the plain is bordered by the Fezouata Oasis and the Drâa River (SES variable RS3, Figure 5.4). The alluvial aquifer is recharged by rainwater collected by surrounding mountains. In this sense, we can consider that actors in Faija SES have clarity on the resource system boundaries (RS2). Groundwater (RU1) is the primary resource. Access to it is mediated by access to collective land, which in turn is managed by tribal institutions. Tribal collective lands are thus another important resource unit to consider to understand the dynamics of groundwater use in Faija. Groundwater is used for agriculture (watermelon is the main crop) through private wells and for drinking water production for Zagora city and territorial communes through public infrastructure operated by the National Office of Water and Electricity (ONEE) (RS4).

According to interviews, there is high uncertainty about future groundwater availability in Faija (RS7) which leads farmers to prefer annual crops (like watermelon) over perennial crops (like palm trees). The groundwater's spatial and temporal heterogeneity (RU7) is influenced by rain events and periods of increased abstraction during watermelon farming (Dec-Apr). Groundwater quality in Faija presents salinity concentrations generally below 1g/l, with an average of 0.6g/l (ABHSMD, 2010:72), which makes this aquifer a very important freshwater resource in the area. Interviewees state that variations in groundwater levels and soil conditions lead to unequal access to this resource among tribe members.

5.5.1.2. Actors

Actors benefiting from groundwater use in Faija are relatively well-defined (A1). We have identified nine distinct actor profiles (Appendix 5.3) that include right-holders of collective lands (tribe members), private land-right-holders; non-land-holders working as investors in watermelon; providers of agricultural inputs; drinking water users of the territorial communes of Zagora, Fezouata, Ternata, Blida and Tamegroute; and governmental actors: ONEE, which operate wells for drinking-water production, and representatives of the Ministry of Interior (Chikh and Moqadem).

These actors vary in economic dependence on the groundwater (A8), interests, socioeconomic attributes (A2), values and norms (A6), and different capacities to access the resource through infrastructure/technology like pumps and solar panels (A9), complicating agreement on resource-use rules. Members of the same tribe (categories I, II, & III, Appendix 5.3) are more homogeneous than non-tribal-actors due to shared social organization based on kinship, customary rules, cultural values, institutions, and reciprocity relations (A2), facilitating easier communication, information sharing (I2), deliberative processes (I3), self-organization (I7), and monitoring (I9). This cohesion also aids leadership emergence (A5). Different tribes do not have a common organization that allows them to communicate and coordinate.

5.5.1.3. Governance system

a. Rules-in-use and rule-making organizations

There are two types of rules regulating access and use of groundwater in Faija: customary rules and statutory rules. The way customary rules were created and implemented fits into the typology of self-governance. These rules focus on collective land, but indirectly they affect access and use of groundwater. These rules are: only members of the tribe can claim use-right over collective land; tribe members need to start farming the land to receive a signed land-use certificate from the tribe and the Caid; it is not allowed to rent land or work with non-tribe members. In 2021, customary rules limited the watermelon irrigated area to 2 ha. per person for every season. This was initiated by the Mssoufa tribe, which appointed a committee for the monitoring of this rule. The Ouled-Aissa tribe replicated this initiative.

Statutory water regulations in Faija operate through a hierarchical, top-down control mechanism, constituting a form of hierarchical governance. These regulations outline the procedures for obtaining licenses to dig wells, designate restricted areas for groundwater extraction, and specify allowable water extraction volumes. They are outlined in the National Water Law 36-15 (Royaume du Maroc, 2016), with ABH-DON establishing specific parameters based on local groundwater conditions. In response to the severe drought conditions affecting the province, the governor of Zagora implemented a regulation in October 2022. This regulation prohibits the cultivation of watermelons and melons in areas exceeding 1 hectare. Moreover, it extends the prohibition to cultivation in areas designated for drinking water supply (Royaume du Maroc, 2022).

In February 2022, different government institutions signed an aquifer contract with representatives of water user associations of farmers in Faija and representatives of the territorial communes benefiting from drinking water production. The contract covers the period from 2022 to 2027 and aims to implement a 45-action plan agreed to achieve sustainable development in the area (Table S 5.1). These actions are organized into five strategic axes resuming the objectives of the contract. These axes aim at **1)** preserving the water reserves of the aquifer, restoring its quantitative balance and exploiting it sustainably; **2)** Protecting and securing the agricultural activity in Faija plain; **3)** maintaining the quality of the groundwater to meet the needs of users; **4)** implementing participatory and consensual management of water resources in the Faija plain and establishing water governance; and **5)** developing a policy for communication and awareness (ABH, 2022). To achieve resource sustainability, this contract aims to limit total water abstractions in Faija to 15 million m³ per year. To this purpose, it foresees the implementation of a mandatory quota system for farmers allocated based on farm size and crop type. According to the contract documents, each well must be declared and equipped with a water meter, and the water police will be responsible for sanctioning users who exceed their authorized water shares. The contract includes strict guidelines to prevent the pollution of resources. Farmers are prohibited from drilling wells within drinking water abstraction perimeters, and collaboration with authorities is mandated to close abandoned wells and boreholes.

The content of the contract was developed by governmental institutions and only later communicated to groundwater users. However, it foresees the active participation of users in monitoring tasks and, presumably, in the allocation of water quotas through water user associations. Given the limited share of power decisions with users, we consider that the Faija aquifer contract cannot be described as conforming to co-governance.

b. Identification of incentives

Here we analyze the regulations that are currently in the process of implementation, notably the ones within the aquifer contract, and the provincial decision, by Zagora's governor, limiting watermelons and melons. Interviews with water users in Faija reveal that customary rules limiting watermelon areas are no longer in place. The rationale behind the abandonment of these customary regulations is elucidated previously.

Table 5.1. Incentives to comply with the aquifer contract of Faija.

Incentive	**Rationale of incentive**
Penalties in case of a 20% over-abstraction (Identified from the interviews). Penalties not yet specified.	A) Disincentivize non-compliance with the rule by creating a cost/burden that exceeds the expected benefits of breaking the rule.
Study on the socio-economic sustainability of the crops grown and the sustainability of irrigation infrastructure	B) Convince farmers to join the aquifer contract by providing technical and financial support to increase and protect economic benefits from agriculture while promoting more sustainable crops (long-term sustainability).
Sensitization to promote the protection of agricultural land.	
Promotion of scientific research: agronomy, optimal crop consumption, innovative irrigation methods, etc.	
Search for new alternative crops with high added value and minimal cost in terms of consumption of irrigation.	
Adoption of new support measures encouraging investment in crops requiring long periods to start the production cycle	
Creation and marketing of a registered trademark for the agricultural product of the Feija Plain for better access to international markets.	
Reduction of intermediaries in the marketing process of local agricultural products and training and support for farmers to access markets and increase their profit margins	
Adoption of specific measures to encourage small farmers	
Establishment of a water quality monitoring network.	C) Promoting trust among water users and between water users and the government by sharing information and engaging the water users in reporting and monitoring actions in Faija.
Creation of an information system on the Feija aquifer	

Within the contract, we identified actions that work as incentives to promote compliance among water users (Table S 5.1). These incentives can be grouped into three categories according to their aims (Table 5.1). First, we identified **A)** penalties that aim at creating a cost/burden that exceeds the expected benefits of not following the specified actions, particularly respecting the water quotas. Interviewees reported that penalties will be applied when exceeding the defined groundwater volume by 20%. In addition, insights from interviews with WUAs representatives suggest that penalties would primarily be monetary. The second group of incentives aims at **B**) providing technical and financial support to participants to increase and protect their economic benefits while promoting a shift to more sustainable crops. Finally, the aquifer contract aims at **C**) promoting trust among water users and between water users and the government through creating a sharing information system and engaging the water users in reporting and monitoring actions in Faija.

The incentive to promote compliance with the limit of 1 ha imposed by Zagora Province on watermelon and melon farms is punitive: the authorities are instructed to destroy the crops that exceed this limit. The local commission responsible for monitoring rule compliance is composed of representatives of the Caidat, municipalities, the royal gendarmerie, auxiliary forces, and farmers. It was appointed by ABH-DON and Zagora Province and may impose additional sanctions on rule-breakers.

5.5.1.4. Faija's focal action situation: outcomes and interactions

In this section we present the outcomes that the Faija SES produces in terms of groundwater management institutional performance, the state of groundwater resources, and in terms of inequality in resource access and capacity to benefit from it. We explain these outcomes as results of particular patterns of actor interaction.

Outcomes

Our investigation finds lax monitoring of groundwater abstraction with no sanctions for violators or water use accountability. Information sharing occurs privately among farmers, lacking formal institutionalized mechanisms to share information between users and the government in aquifer states. Records of private wells are outdated due to a lack of water meters. Users rely on empirical knowledge for groundwater availability.

Faija Aquifer faces an annual deficit of -5Mm³/year, with 34% abstracted from non-renewable reserves. Groundwater levels declined by 12 to 30 meters between the 1980s and 2020 and 34% of groundwater is abstracted from the non-renewable reserve of the aquifer (ABH-DON, 2020). Agricultural pollution degrades groundwater quality, increasing water salinity and treatment costs for drinking water production.

Diminishing groundwater exacerbates social inequalities in resource access. Deeper well requirements raise infrastructural costs, challenging farmers with limited capital. Access to collective land requires mobilizing tribal organizations for land-use rights, but farmers have different influence and power to do this within the tribe. Excessive watermelon production depresses prices, leading to financial losses for farmers.

Interactions

Actors in Faija bypass both customary and statutory rules, notably the 2 hectares limit on watermelon farms set by tribes. Despite a monitoring commission, the tribes lack authority to enforce sanctions, leading to increased rule-breaking. Moreover, different tribes lack shared arrangements for controlling groundwater abstraction, fostering rule non-compliance: interviewees emphasized that it is not worth it for them to follow rules if they have no means to verify whether neighboring tribes are complying with the rules.

Other actors benefit from watermelon production by maintaining the status quo. Despite being prohibited by the tribe, farmers clandestinely rent land to non-tribal investors on watermelon, while intermediary merchants profit from watermelon overproduction by negotiating better prices. Local authorities allegedly benefit from groundwater exploitation through bribes. These bribes are paid by drip-irrigation infrastructure providers and well-drillers who work as intermediaries between farmers and authorities. Drip-irrigation providers help with the application process for subsidies provided by the government. Bribers are to speed up the process to get the required documents. Well-drillers allegedly pay bribes to local authorities to be allowed to dig illegal wells.

Despite a 2022 provincial decision limiting watermelon production, control measures were lacking. Testimonies of interviewees suggest a connection with conflicting interests within the government, which also hinders rule enforcement. While the water sector aims to restrict groundwater abstraction, the Ministry of Agriculture fosters agricultural development, increasing water demand. In turn, the Ministry of Interior Affairs does not strictly enforce the rules because they fear political and social instability in the area as a consequence.

5.5.2. Characterization of the M’hamid case

5.5.2.1. Resource System and Resource Units

In contrast with the Resource System of Faija, the boundaries of the M’hamid aquifer system are diffuse (RS2). For instance, the aquifer recharge does not depend solely on the rain captured and drained in its immediate surroundings, but also on water released from Eddahbi Dam into the Drâa River. In addition, the volume of water allocated to M’hamid Oasis depends not only on the water stored in the dam but on the water, demand estimated for the other upstream oases. As a consequence, despite M’hamid Oasis representing an area of 145 km^2, it can be argued that the M’hamid Aquifer Resource System should include the public infrastructure composed of Eddahbi Dam and the system of irrigation canals that distribute the water along the MDV. According to our interviewees, the absence of water in the river has supposed an important reduction in the aquifer recharge rates (RS5). Other sources of aquifer recharge are water infiltrated due to irrigation and the groundwater flow from upstream oases. This groundwater flow affects the quality of M’hamid groundwater by the cumulative pollution created by upstream water users. Groundwater is used for irrigation, in hotels and touristic facilities, and for drinking water production by the National Office of Water and Electricity (ONEE) (RS1) (see quote N°1, appendix 5.4).

The predictability of the system dynamics is low for the users (RS7). In addition, groundwater availability and quality in Mhamid is spatially heterogeneous (RU7). Aquifer average inflows were determined at 1.3 Mm^3, highly variable water depth (between 79m and 1.60m depth), and low productivity (RS5), with values ranging from less than 0.5 l/s to 12 l/s, with an average of 3 l/s (ABHSMD, 2010). To abstract groundwater for irrigation some farmers dig private wells, but, because for most farmers it is difficult to find groundwater due to scarcity of the resource and the high costs involved in prospecting and digging wells most farmers resort to collective wells (RS4). There are currently five collective wells built in collaboration with "The Mohamed 5 Foundation for Solidarity" in partnership with the Regional Office of Agriculture Development. Other groundwater users, such as hotels, rely exclusively on private wells (See quote N°2, appendix 5.4).

5.5.2.2. Actors

Groundwater users in M'hamid exhibit a diverse profile. This includes domestic users who receive drinking water from ONEE's operated well, farm households, and owners of tourist businesses with varied facilities (A2). While these categories differ in their economic reliance on groundwater resources (A8), individuals within each category share similar interests, contributing to a more cohesive understanding of their specific needs and concerns.

5.5.2.3. Governance system

a. Rules-in-use and rule-making organizations

As in Faija, access and use of groundwater in M'hamid is regulated by customary rules and statutory rules. Customary rules were made by irrigator communities (GS5) gathered around collective wells (Table 5.2). These organizations are built over former communities of irrigators that used to share a surface water irrigation canal and the institutions for water management they used. These organizations have a maximum of 40 members. They agree on the rules to organize the allocation of groundwater abstracted through these wells: the collective well members should pay a membership contribution; water volumes differ per farmer based on previous surface water rights and monthly membership contributions; members should pay a pumping tariff. The collected money is used to cover the costs of fuel and electricity, infrastructure maintenance, and the salary of the well guardian.

Table 5.2. Collective wells rules in M'hamid (GS6) (*source: interviews with farmers in M'hamid*).

Rules	Explanation of the rule
A mandatory contribution fee is levied upon individuals seeking to become potential water users of the communal well.	If a person wants to use water from a communal well, they have to pay a required fee. This fee is used to cover well construction and operation costs, including buying the land to set up the well.
Abstraction fee per hour	Users of the collective-well agree together on a set price, considering what's fair and acceptable to everyone.
Penalties imposed for unauthorized water abstraction	Specific fines are in place for people abstracting more water than established, without paying the fee, or not respecting the quotas established during periods of water shortage.
The funds generated from the abstraction charges are invested in infrastructure maintenance	The money collected from the charges for using the collective well is set aside for the specific purpose of maintaining and improving the shared well for everyone's benefit.

The way these rules were created and implemented fits into the typology of self-governance. These rules are the same in all collective well initiatives within M'hamid according to interviewees involved in the rule-devising process (See quote N°3, appendix 5.4). Collective well organizations are independent from each other and there is no overarching organization to articulate all these collective wells. Neither to coordinate between collective wells and other actors benefiting from groundwater in M'hamid, such as owners of tourist facilities and ONEE. Statutory rules are the same as described in the case of Faija (water laws n° 19-95 and n° 36-15, hierarchical governance).

b. <u>Identification of Incentives</u>

Within the collective well rules proposed by the local communities, two incentives to limit groundwater use were identified. First, the abstraction fee per hour is an incentive and a motivation for water users to abstract only as much as needed and sufficient for their production. The more they abstract, the more they will need to pay. Second, penalties. These are proposed by the local board of communities for those who engage in unauthorized pumping from collective wells without fulfilling the requisite pumping fee obligations. This rule aims to discourage and control illegal water abstractions from the collective well.

5.5.2.4. M'hamid focal action situation: outcomes and interactions

Outcomes

According to interviewees, the state of the M'hamid aquifer is degrading. The salinity of the M'hamid water table varies, increasing in downstream direction, reaching a maximum level of 12.16g/l, (O2) (ABHSMD, 2010: 107). The groundwater inflows and outflows were estimated in 2010 at a balance point of 225.4 l/s (ABHSMD, 2010: 107), however, interviewees reported a constant decrease in the levels of groundwater tables in wells (see quote N°4, appendix 5.4).

Interviewees reported that most landholders in M'hamid do not have access to irrigation water. Their gardens have dried up, the household's economy has deteriorated, and several families have been forced to migrate. Emigration has altered the local social dynamics in the villages since only women, children, and old people are left behind. Young men live and work in cities (O1, O2). Interviews report that in recent years agricultural yields have decreased significantly and farmers are reducing the number of crops. As a consequence, monetary incomes from agriculture have reduced significantly and farmers produce mainly for self-consumption. Because cash is necessary for inputs in each agricultural campaign, households depend on other sources of income such as family members' remittances, retirement pensions, or salaries from other activities. The main economic activity is shifting from agriculture to tourism.

In terms of institutional performance, there is a notable absence of formal mechanisms for regular and systematic information exchange regarding the condition of the aquifer between users and authorities. The only existing platforms for information sharing regarding groundwater availability and infrastructure maintenance responsibilities are the collective well organizations dedicated to irrigation. However, these platforms are limited to communication among users associated with each specific well. Within these collective well organizations, the appointed board receives reports from the well guards regarding unauthorized water extraction and determines appropriate penalties or sanctions. Nevertheless, there is a lack of overarching institutions to monitor and disseminate information regarding aquifer conditions and groundwater extraction practices among users of different collective wells. This absence hampers comprehensive decision-making processes that incorporate input from all groundwater users concerning the M'hamid Aquifer as a unified entity remains severely limited.

Interactions
Collective-well organizations for irrigation provide a platform to share information about the availability of groundwater, the resources used by users, and the fulfillment of users' responsibilities in the infrastructure maintenance, but only among the users of each well. The designated collective well board receives reports on unauthorized water extraction and decides on suitable penalties or sanctions for each case. There are no overarching institutions to monitor and share information about the aquifer state and groundwater abstraction practices between users of different collective wells or to facilitate decision-making that includes all groundwater users sharing the aquifer. As a consequence, information about the impact that the different groundwater abstraction practices have on the resource or decision-making regarding the M'hamid Aquifer as a unit is very limited.

5.5.3. Characterization of the Fezouata case

5.5.3.1. Resource System and Resource Units

Fezouata is an alluvial aquifer located South of Zagora City (RS9) and extends over an area of 167 km². Its catchment has an area of 447.6 km² (RS3) (ABHSMD, 2010: 77, 80). However, similar to M'hamid, the recharge of Fezouata aquifer is affected by water availability in the Drâa River, which is directly affected by water releases from Eddahbi Dam and the water consumption of upstream users. In Fezouata, groundwater is used for irrigation of diversified agriculture, drinking water production carried out by ONEE, and domestic usage (RS1). Local inhabitants use private wells, while ONEE works with public infrastructure (RS4).

Middle and long-term groundwater availability is very uncertain for the users (RS7). In addition, groundwater flow rates are unequally distributed in Fezouata, facilitating better groundwater access for some farmers (RU7). Recharge rates vary from less than 1 l/s to 15 l/s, with an average of 5 l/s. High-productivity areas (over 10 l/s) are generally located along the valley close to the flow axis of the river (RS5). Abstraction for drinking water supply was estimated at 21.9 l/s for a population of 34,162 inhabitants, while agricultural withdrawals were estimated at 13.86 Mm3 (ABHSMD, 2010).

5.5.3.2. Actors

Groundwater users of Fezouata present a heterogeneous profile. There are farm households, hotel owners, and households using groundwater for basic needs which don't include domestic water users. However, there is no official record of the exact number of relevant users (A2). Interviewees estimate the number of farmers between 3000 and 4,000 people. Due to the scarcity of surface water, it can be assumed that all farmers have access to groundwater (RU3). Groundwater is used to irrigate market-oriented crops (date palms, almonds, alfalfa) (RU6) and vegetables for self-consumption (A8). Access to groundwater in Fezouata does not depend on resource availability only, but also on access to the capital to build and deepen wells. For this purpose, local inhabitants count on the commerce of dates and other crops (RU4), remittances from family members, and side jobs (i.e. construction sector) as income sources. As a consequence, some water users have better access to groundwater than others.

5.5.3.3. Governance system

a. Rules-in-use: Statutory laws

There are no community-based institutions aimed at regulating the use of groundwater. The only regulatory framework in place over access and use of groundwater is the laws provided by the Moroccan government (hierarchical governance) (GS5). Individual private groundwater exploitation within Fezouata adheres to the state regulations (Table 5.3) defined in the Moroccan water laws n° 19-95 (1995) and n°36-15 (2016) (GS6). These rules were in place for decades and according to interviewees, the majority of the water users in Fezouata are well-informed of these regulations.

Table 5.3. State regulations for groundwater exploitation in Fezouata (GS6).

Rules and regulations (water laws n° 19-95 and n° 36-15)	**Explanation of the rule**
Obtaining official authorization from the Basin agency before any groundwater utilization (Article 26, law 19-95).	The rule states that before using groundwater, you need to get permission from the Basin agency (ABH-DON).
Authorization has to encompass parameters such as water discharge rate, volume allocation, agricultural area designated for exploitation, and associated financial dues (Article 39, law 19-95; Article 27 and 31, law 36-15).	The rule states that the permission request needs to cover specific details such as how much water can be used, how it will be distributed, the areas that will be irrigated, and the fees or payments associated with using the water.
The Basin agency retains the authority to remove authorizations under circumstances defined within the legal framework (Article 39, law 19-95; Article 32, law 36-15).	The rule means that the Basin agency has the power to cancel or take away the permission they previously granted for using groundwater if certain conditions described in the law allow them to do so.
Certain violations can lead to sanctions being imposed in alignment with the established guidelines (law 36-15).	The rule states that if certain rules were broken, water users may face penalties according to the rules that have already been set.

b. Incentives identified within the rules

Incentives in law n° 19-95 and n° 36-15 include primarily penalties. The penalties are imposed in the event of owning an unauthorized well, serving as a deterrent against illegal water extraction practices. In addition, legislation 36-15 promotes the adoption of water-efficient technologies as part of the national water strategy 2020-2025. For instance, the government offers financial support for the installation of solar panels under specific conditions, aimed at encouraging sustainable practices among farmers. To grant this support, farmers are required to have authorization for their wells, which, in theory, should encourage farmers to declare their wells and comply with the rules presented in Table 5.3.

5.5.3.4. Fezouata focal action situation: outcomes and interactions

Outcomes

In relation to the state of the resource, in 2010 ABHSMD reported that inflows and outflows of the Fezouata aquifer were in balance (542.3 l/s). However, interviewed local inhabitants (2021-2023) explain that the water table of the aquifer has dropped significantly during the last years due to prolonged droughts, that reduced the aquifer recharge rate, and over-abstraction of groundwater by farmers (O2).

Groundwater is unequally distributed in Fezouata's territory, which leads to unequal access to this resource among local inhabitants (O1). In addition, access to groundwater depends on access to capital to dig deeper wells and social networks to avoid sanctions for unauthorized wells. Interviews suggest that this is leading to widening social gaps.

Concerning the institutional performance, the statutory regulation in place is loosely monitored and there are no actual sanctions for infractors. Consequently, there is no accountability for groundwater use. Formal institutions dedicated to the dissemination of information among local water users on the aquifer's condition, water table levels, and areas within Fezouata experiencing water scarcity are conspicuously absent. This information is regularly exchanged through informal conversations among neighbors and friends based on their empirical observations. The Jemaâ, a local community board, is not particularly focused on groundwater management. In collaboration with the Moqadem in each douar, the Jemaâ assumes the primary responsibility for resolving conflicts of any nature that may arise within the area.

Interactions

In Fezouata, groundwater is treated as a private good. Interviewees report that the reduction in water levels has been steady over the last decades, however, they used to have enough water to share with friends and neighbors. Collective wells were not necessary. It has been only in recent years, according to these testimonies, that the situation of groundwater scarcity is turning critical. Water sharing has reduced dramatically because well owners can barely get enough water for themselves. Interviewees foresee a scenario similar to that of M'hamid: emigration and abandonment of farms.

In summary, the three SESs studied exhibit varying governance systems, responding to different challenges under varying conditions (Table 5.4, Appendix 5.5). M'hamid faces the most severe degradation among the three, characterized by markedly high salinity levels, groundwater scarcity, and low recharge rates. Consequently, accessing groundwater becomes challenging, encouraging the urgency for joint efforts and shared extraction sources. Fezouata also displays depletion signs through decreased agricultural production, numerous dry and abandoned farms, and wells. Despite these signs, private wells persist and no groundwater management collective action has been developed. In contrast, the Faija Aquifer presents better water quality and, despite the aquifer being declared in deficit, farmers are still able to abstract significant water volumes. In M'hamid and Fezouata, the aquifer systems boundaries are fuzzy, making it difficult to identify the relevant stakeholders that should participate in governance institutions, hindering the establishment of concrete management mechanisms oriented to achieve resource sustainability. The diffuse user community also contributes to this challenge in Fezouata. Each governance system pursues varied objectives, not necessarily aligned with resource sustainability. For instance, M'hamid users prioritize resource access and allocation, while in Faija and Fezouata rules aim at sustainability within their regulations.

Table 5.4. Summary of key differences among the three SESs.

Case	Groundwater institutions	The objective of groundwater institutions	System boundaries/size	Perception aquifer state
Faija	Aquifer contract	Resource sustainability; Protection of agriculture.	Clear aquifer boundaries; Clear user community	. Awareness of drop in water tables by farmers; . Farmers still find enough water for their farming activities.
Fezouata	Statutory laws (No self-governance)	Resource sustainability	. Diffuse aquifer boundaries; . Diffuse user community;	. Aquifers show signs of depletion; . Farmers are still able to find water in private wells;
M'hamid	Self-governance organization of collective wells.	Provide access to groundwater and a fair water allocation	. Diffuse aquifer boundaries; . Clear user communities.	. Farmers find it very difficult to find enough groundwater of good quality.

5.6. Discussion

5.6.1. Adequacy analysis of the incentives: Factors affecting rule-compliance

The analysis of incentives reveals challenges in achieving rule compliance in both Faija and Fezouata. In Faija, farmers express concerns about the immediate financial impacts of aquifer regulations, fearing constraints on groundwater access, debt settlement, and profits. Studies indicate that farmers base their water use decisions, crop selection, and adherence to regulations on perceived risks and cost-benefit assessments (Vignola et al., 2010; Michetti et al., 2019; Alcón et al., 2019; Vásquez, 2020; Mitra et al., 2021; Bagheri and Teymouri, 2022). Notably, farmers openly oppose the government's initiative to install water meters in their wells as part of water quota enforcement efforts (see section 5.5.1). Our analysis suggests that imposing significant legal penalties (Table 5.1) could encourage compliance with water quota limits. However, if the benefits of breaking the rules outweigh the penalties, farmers may choose to pay the penalties regardless. Weak monitoring and rule circumvention, as reported by interviewees, undermine the efficacy of penalties, aligning with previous findings in other regions in Morocco (Houdret & Heinz, 2022). This underscores the limited effectiveness of penalties as legal incentives for groundwater rule adherence. Scholars have argued similarly that state-centered groundwater governance and penalty imposition often yield limited success (Theesfeld, 2010; Holly and Sinclair, 2012; Greiner et al., 2016; Schoengold and Brozovic, 2018; Molle and Closas, 2020; Penny et al., 2021).

Furthermore, incentives providing technical and financial support to promote sustainable practices could mitigate the impact of water restrictions on farmers by improving water efficiency and economic returns. Specifically, farmers in Category I (Appendix 5.3) expressed the need for assistance and guidance to identify and rectify bad farming practices (See Molle and Tanouti, 2017). Therefore, educational initiatives could enable governments to impose modest water restrictions on Faija farms. Greiner et al. (2016) reached a similar conclusion in their study on irrigation water use in Australia, highlighting that education and information foster spontaneous compliance among a majority of water users (See also Sullivan et al., 2003; Ostrovskaya et al., 2013; Euler et al., 2018; Petit et al., 2021). Additionally, challenges encountered by farmers in the watermelon market, such as the proliferation of intermediaries and profitability optimization difficulties, suggest that streamlining markets and assisting with marketing strategies could enhance farmers' economic outlook, incentivizing compliance with regulations outlined in the aquifer contract.

Our analysis reveals that in Fezouata there is a disconnection between statutory regulations and conditions of farmers, which result in a poor capacity to comply with the rules. Farmers find the process of getting well licenses time-consuming, costly, confusing, and often unproductive. In addition, weak monitoring and sanctioning reduces the intended effectiveness of penalties as rule-compliance incentives. Interviewees among farmers and governmental representatives report that this situation leads to the proliferation of illegal wells. Recent research on the topic has reached similar findings about the effects of administrative burdens as primary barriers to rule compliance among California's farmers (Bodwitch et al., 2021). In addition, our data also shows that the access to water-efficient technologies promoted through the national water strategy (2020-2050), has limited capacity of local authorities to incentivize compliance, as farmers could access them without legalizing their wells. This aligns with similar challenges in other Moroccan regions (Kuper et al., 2016; Houdret & Heinz, 2022).

Molle and Closas (2019) highlight constraints in state-centered groundwater governance, citing challenges in monitoring diffuse users, financial and logistical challenges, as well as conflicting private interests that are inconsistent with the longer-term common good. Interviews with farmers and governmental officials echoed similar limitations, citing financial and human resource constraints, as well as the political and social costs of stricter rule enforcement. Resolving financial and human limitations might involve increased budget allocation, but addressing political and social costs, tied to broader national agendas, poses greater challenges (Houdret, 2012).

The incentive adequacy analysis for M'hamid shows that the shared perceptions of resource scarcity drive compliance with self-governance rules, fostering strong community engagement and reducing reliance on penalties. Interviewees stressed that the collective-well rules balance and address the interests of the user groups reliant on the communal well. According to the interviews, penalties hold a minimal but effective role. This is primarily because penalties always outweigh the potential benefits of breaking the rules. Second, small group size dynamics ensure monitoring and easy identification of free-riders, which discourages rule violations. Third, penalties emphasize the importance of rules, ensuring fairness and equity. This aligns with findings from similar contexts (Cody et al., 2015). Overall, penalties are viewed as a last resort, with community engagement as the primary approach for voluntary compliance.

5.6.2. Opportunities and limitations of groundwater self-governance

According to the Common Pool Resources (CPR) literature, self-governance often emerges from the presence of a credible threat to the existing status quo (of the SES) if no action is taken (Ostrom, 2009; Cody et al., 2015; Molle & Closas, 2020; Shalsi et al., 2022). Sustainable resource use, in turn, emerges as a result of implementing rules limiting over-use and from the fact that most users believe in the necessity and efficacy of the rules (Ostrom, 2009). In our three cases, all interviewees voiced aquifer degradation concerns, yet Fezouata stands out for lacking self-governance organizations. This difference might indicate that groundwater users of Fezouata perceived a lesser threat over the resources and lesser urgency to act compared to users of M'hamid and Faija. Alternatively, it may suggest that a perceived threat to the status quo is not enough to trigger a self-governance organization.

In M'hamid, farmers' struggles to access groundwater coupled with acute surface water scarcity, which results in an immediate need for collective action to secure access to water. However, the focus of this collective action is primarily on locating groundwater and establishing affordable means of extraction rather than achieving resource sustainability. For instance, collective wells do not include mechanisms to ensure that total abstractions do not exceed aquifer recharge. Results show that in Faija, declining groundwater levels play a smaller role in the emergence of self-governance compared to M'hamid, highlighting instead tribal identity and pre-existent collective institutions' importance. Through a process of "commoning", tribe members rally under a narrative of safeguarding the shared Faija aquifer against outsiders who overabstract the resource (Bossenbroek et al., 2023). Yet, enforcing rules promoted by tribe members remains a challenge, limiting the effectiveness of this self-governance approach (see section 5.5.1). Additional factors likely influencing the emergence of self-governance organizations in the MDV necessitate further investigation.

Following this rationale, Fezouata's lack of groundwater self-governance might be attributed not just to a lower urgency in limiting groundwater use but also to its privately-owned land regime. Unlike areas where tribal permissions regulate land access and groundwater use, Fezouata lacks this organizational structure, leaving farmers without a coordinated platform to discuss or monitor groundwater activities in the territory. In comparison to Faija, Fezouata suffers from ambiguous community and resource boundaries, which hinder the emergence of self-governance, as described in CPR theory (Cox et al., 2010). Both Fezouata and M'hamid face complexity in their big groundwater systems due to the influence of the Eddahbi Dam and connection with upstream aquifers, leading to unclear system boundaries.

5.6.3. Limitations for developing a unified groundwater governance system

The results indicate that groundwater users in the M'hamid and Faija aquifers have established self-governance organizations to formulate and oversee rules. However, these organizations operate independently of each other, lacking the ability to coordinate rule creation, monitor compliance, enforce sanctions against violators, and implement conflict resolution mechanisms across broader spatial scales. Consequently, effectively limiting groundwater extraction for all users sharing the same aquifer remains challenging. CPR studies offer extensive evidence emphasizing the importance of coordination and information sharing in fostering trust among resource users, legitimizing governance systems, and ensuring rule compliance (Ostrom, 1990; Cox et al., 2010).

As a response to groundwater depletion problems, the Moroccan government is promoting aquifer contracts along the country as an institutional framework to integrate the actions of localized self-governance organizations with the actions of governmental organizations. As part of these contracts, water user associations (WUAs) are meant to play the role of local groundwater management organizations in charge of allocating water quotas among their members and monitoring water use. By participating in this institutional framework, farmers are expected to gain access to information on the state of the aquifer and the behavior of other aquifer users, which is intended to increase trust in the management system and its legitimacy and enhance rule compliance. It is not clear if WUAs will also monitor the water use of other associations.

For this approach to succeed, effective coordination among Water User Associations (WUAs) within each aquifer and between these WUAs and government institutions is essential. Achieving this coordination necessitates strong incentives or a high level of trust (Baldwin et al., 2018). One potential motivation for downstream users to engage in aquifer contracts is their belief that upstream water extractions impact them, thus requiring rules to regulate and monitor these extractions. However, our interviews indicate a very limited understanding of aquifer dynamics among users, which may impede consensus on the need for coordination among localized self-governance organizations. Additionally, upstream users may not perceive the need to participate if their water usage remains unaffected by downstream actions. Prior research indicates that upstream user involvement often stems from the need to establish mechanisms to prevent and resolve water conflicts (Baldwin et al., 2018). In the Faija, inter-tribal conflicts primarily revolve around collective land control rather than water resources. This history of conflict could hinder trust-building for water governance rather than fostering awareness of the benefits of aquifer contracts. Interestingly, there have been no recorded water conflicts between different collective wells in M’hamid. However, both cases indicate a lack of inherent motivation among upstream users to engage in institutional coordination with downstream users. Therefore, simply establishing monitoring systems may not suffice to encourage upstream participation; more detailed implementation plans are required.

5.6.4. The SESF application

The use of the SESF in characterizing the aquifer cases has been pivotal in our research. It has enabled us to identify relevant variables crucial for explaining institutional arrangements within the three SES analyzed, while navigating the complexities and capturing necessary interactions for our analysis. Moreover, augmenting the SESF with an incentive structure analysis has significantly enriched our exploration. In the CPR literature, the SESF is often used alongside Ostrom’s design principles (1990) to evaluate the emergence of sustainable self-governance systems, including conditions motivating rule compliance—similar to the incentive analysis approach. However, while design principles focus on self-governance regulations, incentive analysis extends its applicability to various types of regulations across self-governance, hierarchical governance, and co-governance systems. This versatility makes the combination of SESF with incentive structure analysis advantageous and has strengthened our analysis.

We acknowledge the blind spots that scholars, notably critical institutionalists, have pointed out for the application of the SESF. First, this analytical framework relies on the assumption that individuals and organizations act rationally based on costs and benefits. However, human behavior may be influenced by a myriad of factors beyond a simple rational choice model, such as emotional, moral, and social rationalities informed by differing logics and world views (Cleaver, 2000; Cleaver & de Koning, 2015). Furthermore, the SESF and incentive analyses may not fully capture how power dynamics shape decision-making and rule compliance (Herdt and Sardan, 2015). Finally, the frameworks’ static nature, focusing on a singular point in time, raises concerns about their ability to capture the dynamic evolution of SESs and the impact of incentives over time (Cleaver & de Koning, 2015). To better understand these aspects, further research is required.

5.7. Conclusions

Our analysis indicates that while groundwater users in each case study face typical common pool resource governance challenges such as equitable water allocation and resource sustainability, they have developed distinct institutional responses. These differences in institutional arrangements are closely tied to the unique characteristics of each Social-Ecological System (SES), including biophysical attributes and actor characteristics. Consequently, the governance systems inherent to each SES possess specific limitations.

For instance, the hierarchical approach that prevails in Fezouata faces significant challenges in attaining rule compliance, which compromises in turn the capacity of the system to achieve resource sustainability and equitable resource distribution. This is primarily due to the discrepancy between state regulations and local realities, necessitating adjusting the design of the incentives, but also to weak sanctioning, which reduces dramatically the efficacy of incentives. In contrast, self-governance, observed in M'hamid and Faija, demonstrates an advantage in terms of rule compliance. This is attributed to well-defined user communities that have mutually agreed on the importance of regulating resource use in their best interest. However, self-governance organizations may not prioritize long-term resource sustainability (as evident in the M'hamid case) and may lack the authority and legitimacy to effectively sanction rule violators, compromising rule compliance (as seen in the Faija case). Consequently, users often demand state intervention in the sanctioning process. Secondly, the inability to sanction rule violators underscores the necessity of a unified governance system that coordinates the actions of these organizations with those of the state, supporting sustainable practices while enhancing the authority and legitimacy of local bodies for effective regulation enforcement.

Aquifer contracts could provide the institutional framework to develop a unified system as such at the aquifer level. However, engaging local actors in rule formulation is imperative, a vital yet missing aspect observed in the Faija aquifer contract, compromising its effectiveness. Overcoming this limitation demands active participation and co-creation of rules by local stakeholders. Nevertheless, implementing a unified governance system in each aquifer also faces the lack of natural incentives among resource users to participate in such a system, particularly among upstream users. Addressing this challenge could involve the introduction of compensatory measures tailored to mitigate the lack of natural incentives and encourage broader participation across stakeholder groups, ultimately fostering a more inclusive and effective groundwater management system.

Finally, the diversity of governance institutional arrangements addressed in this paper advocates for context-specific analyses to inform effective groundwater management and incentive-based policies. In this sense, the application of the SESF proved valuable in addressing the particular problems of groundwater governance in the MDV. Its utilization provided a comprehensive lens through which we could dissect and comprehend the interplay between key variables within the context of each study area. The SESF offered a structured and holistic approach, enabling us to identify, analyze, and ultimately navigate the complexities inherent to groundwater governance, thereby enriching our understanding and findings within this research.

Chapter 6

Conclusions and Recommendations

6.1. Summary of main research findings

In the Middle Drâa Valley (MDV), there are escalating demands for essential water ecosystem services, essentially the provisioning services, which clash with deteriorating river and oasis ecosystems. These issues are exacerbated by climate extremes, intensified agricultural practices, population growth, and urbanization. While intensive agriculture contributes to economic development and food security, it also poses numerous environmental and social challenges. Human-engineered systems like the El Mansour Eddahbi Dam and Agdz Dam have enhanced water availability for drinking and irrigation in arid regions. However, this comes at the cost of degrading and modifying river ecosystems that provide a wide range of ESS, including regulating and cultural services. This has led to a shift from surface water to extensive overexploitation of groundwater for irrigation purposes. The main question is how to best manage the Drâa water resources to maximize the overall productivity of ESS and ensure their long-term contributions to local communities' well-being. This dissertation aims to address this question by using the ESS concept within a social-ecological system framework, providing insights and context-specific data from the arid Middle Drâa Valley. The research questions to be answered are: *How can the notion of ESS contribute to understanding human-water relations in an arid context? How can the economic valuation of ecosystem services inform local water decision-making processes? What are the advantages and limitations of these approaches? What are the opportunities and challenges of groundwater governance in the MDV to sustain the water-related ESS supply?*

A comparison of water-ESS perceptions of governmental actors and local inhabitants in the MDV is conducted in Chapter 2. The research revealed that while both groups prioritize provisioning services like drinking water and irrigation, there are notable differences in their perceptions of regulating services and cultural services. This suggests that assessing ESS perceptions can enhance stakeholder learning and dialogue about trade-offs, especially under climatic variations, and underscores the importance of considering power dynamics and governance structures. Reflecting on generic policy principles for ESS supply resilience, we believe that by assessing ESS perception, stakeholders can learn from each other and make informed decisions bout water resource management. This process can promote broader participation in real-world settings, including traditional and modern institutions and diverse water users, as well as deriving recommendations for Drâa Valley water resource management. This will help facilitate a common dialogue on ESS trade-offs. The influence of power dynamics has to be taken into consideration in both processes.

In the MDV, the majority of locals are particularly concerned with securing adequate water quantity and quality for agriculture. In this arid region, they often seek alternative water sources when surface water from dam releases or rain is insufficient. Chapter 3, therefore, focuses on the economic valuation of irrigation water service, rated the most important of the ESS identified in the previous chapter for its vital role in the livelihoods of local communities in the area. As explained in Chapter 1, an indirect revealed preference method was possible and more suited for the specific context of the research area. In particular, the growing activity of well-digging and the shift from surface water use for irrigation inspired the testing of the replacement cost approach, assuming that it may help reflect partly the ESS loss value. The research estimates the costs incurred by farmers to install wells as a substitute for declining irrigation water from the Drâa River, highlighting disparities among and within oases through cost assessments.

The main findings in Chapter 3 show that the losses incurred from the reduced surface water did not follow the aridity gradient, and varied due to water regulation practices, investment capacity, other income-generating activities, and other factors. The regression analysis suggests that large farms are willing to invest more, on average, to replace surface irrigation water used for irrigation. It also suggests that the effect of farm size on the total replacement cost differs for Fezouata, Zagora, and Ternata oases as compared to Agdz, where this effect is more pronounced. In Zagora, the farm size effect may turn slightly negative, indicating that larger farms there tend to invest a bit less in drilling wells, which could be due to different local conditions or strategies. The analysis also suggests that the replacement is cheap per unit of meters dug, hectares, and kg of dates, providing an advantage in terms of economy of scale for large farms according to regression models B1, B2, and B3. Higher production of dates tends to lower the overall replacement cost of a farm, but at the same time, higher benefits from date commerce increase the replacement cost. So, while higher production of dates may lead to cost savings, which in this case can be explained by post-harvest storage time, the increase in benefits from selling in better-market conditions might also entail additional irrigation costs (e.g. upgrading pumping equipment in the wells or even administrative costs). Farmers exclusively using groundwater for irrigation may be more willing to pay for it due to its perceived reliability compared to those also using dam releases. Additionally, larger families might be less willing to invest in irrigation water because they are more engaged in non-agricultural activities or rely on remittances from family members working elsewhere.

Testing the RCA revealed the extent of losses experienced by farm households along the Middle Drâa Valley. However, data limitations present challenges and highlight the inadequacy of the method for accurately estimating ESS loss value in the context of the research. It is possible that other factors explain the motivations of local communities to access groundwater, and that compensating for ESS losses is not the sole motivation. This underscores the need for future research to refine estimations and fully understand the impacts of water scarcity in the MDV considering all possible variables. The analysis emphasizes the relevance of understanding farmers' responses to water scarcity. It also suggests considering the socio-economic impacts of water scarcity on different oasis areas and promoting policies that support sustainable water resource management.

Chapter 4 explores the notion of ecosystem health and its connection to human well-being. The impact of high salinity levels and low water flow on the water quality, biological quality of rivers, and human well-being in the Drâa River basin is examined. The analysis indicates direct and indirect relationships between the state of the river ecosystem and human well-being, noting that saline river water can cause emotional distress and reduce satisfaction. Salinity in drinking water was reported to be linked to kidney diseases in the lower Drâa, with every tenth person reporting negative effects from water such as fecal-oral diseases and tooth discoloration. However, these effects may not be directly caused by river water, as the bacteriological quality of water could change between the source and point-of-use (i.e. from aquifer to storage tower or taps in households). In addition to physical diseases, people reported experiencing emotional distress due to water salinity and scarcity in the Upper, Middle, and Lower Drâa. Witnessing wetland degradation is a plausible explanatory factor for the emotional distress people experience while living in the area. The analysis highlights the challenges in understanding and establishing a definitive link between ecosystem status and well-being, suggesting potential influences from factors like cultural background, local needs, or water usage. More comprehensive surveys, detailed open-ended interview questions, and complex statistical tools may be necessary to uncover these associations, emphasizing the need for a larger sample size.

In Chapter 5, the focus on groundwater continues by exploring different groundwater governance systems using incentive structure analysis. Findings reveal the benefits and drawbacks of current hierarchical and self-governance models identified through three case studies in the MDV. The incentive analysis of governance rules and laws shows that the hierarchical model in Fezouata SES struggles with rule compliance due to discrepancies between state regulations and local realities, as well as weak sanctioning mechanisms, reducing the efficacy of incentives. In contrast, self-governance in M'hamid and partly in Faija exhibits advantages in rule compliance due to well-defined user communities with mutual agreement on resource use regulations, resulting in a low need for legal incentives, notably penalties. However, self-governance encounters limitations in prioritizing long-term sustainability and enforcing rules effectively. The aquifer contract in Faija, currently undergoing implementation, combines hierarchical and self-governance models. Results show inadequacy of several proposed incentives within the aquifer contract, posing more risks of non-compliance with rules due to lax enforcement and sanctions. While aquifer contracts can potentially coordinate local and state actions, the lack of active participation of local stakeholders in rule formulation in Faija may compromise its effectiveness, particularly regarding rule acceptance and compliance. This highlights the need for natural incentives for locals' participation in such agreements, and the importance of addressing this issue, notably through compensatory measures. This combined approach suggests that adaptive governance aligned with local contexts, can foster a more inclusive and effective groundwater management system, ultimately supporting the sustainability of the MDV.

The research findings provide some insights into the challenges and dynamics present in the arid SES of the MDV when addressing the research questions. They demonstrate the practical application of the ESS concept, revealing the intricate connections between water ecosystems, ESS, human well-being, and governance processes. These findings offer a basis for drawing diverse conclusions and recommendations.

6.2. General conclusions, recommendations, and contributions in the research field

The findings of the present dissertation reveal several key conclusions. Firstly, assessing and contrasting ESS perceptions among different stakeholder groups is crucial for understanding and improving resource management. Moreover, the disparities in water-ESS perceptions between key stakeholder groups present an opportunity for communication and collaboration in water allocation discussions. Addressing these disparities is essential to enhance the supply and resilience of various services crucial for the ecosystem and local livelihoods in the Drâa basin. This can be achieved through inclusive and participatory water management decision-making processes which should consider the diverse perspectives and needs of all stakeholders. For instance, multi-stakeholder meetings and forums where representatives from various groups can voice their concerns and priorities are recommended. To ensure all stakeholders have the knowledge and the tools to participate effectively, capacity-building activities might be needed especially in the context of the MDV where locals might lack such tools. This might foster meaningful stakeholder participation is essential for securing effective outcomes of decision-making and benefit-sharing around ecosystem management and use (e.g. Esguerra et al., 2017; Kurg et al., 2020).

Consideration of power dynamics in these processes is critical and recommended. In situations where regional governmental actors glean insights and learn from locals, such as farmers (Chapter 2), farmers may be seen as non-experts due to existing power dynamics. Powerful governmental actors can significantly influence which perspectives are included or disregarded. Equally significant are the implications of power imbalances on the involvement of local communities alongside governmental actors in water management, potentially limiting their contribution to the overall management framework. An example of the impact of power imbalance is evident in the Faija aquifer contract case (Chapter 5), where local water users had minimal or no participation in rule formulation despite the contract's initial participatory intent. Efforts are required to convince actors of the importance of adopting an actual participatory approach in their decision-making process. Making the value of incorporating local perspectives visible requires further research in the context of the MDV. Common views among stakeholder groups can serve as a starting point for fostering more inclusive and effective water management practices in the Drâa basin. By leveraging shared interests and goals, again through meetings, forums, participatory monitoring, training programs, and regular information sharing, consensus can be built and collaborative action might be driven.

Secondly, the economic valuation of surface irrigation water in Chapter 3 highlighted the importance of this service for MDV communities. It helped estimate the losses they faced when the supply of surface water decreased, leading to their adaptation actions to access groundwater as an alternative. The analysis shows that small-scale farms in all the oases experienced significant losses, with those situated in the lower Drâa Valley being the most affected by drought and reduced water availability. This insight not only identifies the oases facing the most substantial challenges but also provides a valuable guide for future water allocation decisions in the MDV.

In this sense, the development of targeted incentives and programs aimed at supporting effective water management in the MDV are needed and recommended. This might include the adoption of drought-resistant crop varieties and water-saving irrigation techniques, as well as the adjustment of current water management policies or implementation of new ones. More specifically, subsidies for water-saving technologies for oasis farmers, access to low-interest loans, trainings and education programs on the use of these technologies and on farming cost management, as well as on water usage monitoring systems (e.g. water sensors and meters) to track water consumption patterns and identify inefficient practices can contribute to an effective water management immensely. In addition to that, developing adaptable water allocation strategies based on changing climate and water availability could be advantageous, especially considering projected temperature increases and precipitation pattern shifts. Further, the analysis calls for measures to address unequal access to water. For instance, the development of equitable water allocation policies to reach all parts of the valley, infrastructure development to improve water delivery and storage, as well as the establishment of community-based water management committees to address this issue locally, particularly in oases facing substantial challenges. Crop selection is also crucial. Encouraging the cultivation of water-efficient and economically viable crops can help farmers reduce their losses. Studies in drought-affected Mediterranean regions have suggested crops such as carob trees, almonds, and figs, which are both drought-resistant and economically valuable. The carob tree has been highlighted during interviews as a potential alternative in the MDV. By implementing these targeted incentives and addressing disparities in water access, a more equitable and efficient water allocation system could be achieved.

Thirdly, the analysis of groundwater governance systems in the MDV revealed that institutional diversity reflects variations in the social-ecological systems of each area, demonstrating that a single system can't work for all. It can be inferred that self-governance organizations in the MDV offer a significant opportunity for regulating groundwater use compared to hierarchical modes. However, these organizations may not always prioritize long-term resource sustainability, as evident in the M'hamid case, and may lack the authority and legitimacy to effectively enforce rules, leading to compliance issues as observed in the Faija case. In such instances, users often turn to the state for intervention in the enforcement process. A recommendation in this context would be to establish a cohesive and unified governance system, that aligns and coordinates the efforts of all local organizations with the state. While collaboration with government institutions is encouraged, it should be structured in a way that preserves the autonomy of organizations to create rules and engage in self-monitoring.

The aquifer contract in Faija is seen as an institutional framework that could be used to develop a cohesive and unified system. However, this potential may be compromised by the lack of local stakeholder engagement and limited delegation of decision-making power during the design process of the aquifer contract. Chapter 5 research highlights the imperative role of incentives and the need for careful design to motivate users to change their behavior and increase compliance and urgency in resource use rationalization, especially in water-stressed areas like the MDV. Incentive-based tools can help policy-makers strategically encourage desired behaviors and discourage undesirable ones, as well as identify areas for incentive adjustments to achieve desired outcomes.

Policymakers have the responsibility to establish clear and measurable goals for the incentives they create. They should be willing to adjust incentives based on results, use a variety of incentives to target different aspects and balance the various priorities of resource users. When designing incentives, policymakers should consider the long-term effects, assess the efficiency of these incentives, evaluate potential unintended consequences, and plan for the gradual phasing out of incentives as desired behaviors become normalized (e.g. Adams et al., 2017). For instance, if financial rewards are offered for certain actions, the amount or frequency of these rewards can be reduced over time to ensure that the behaviors continue even without the incentives. In the case of groundwater use in Faija, it may take some time to observe the consequences of incentive implementation due to complex aquifer dynamics and the time needed for farmers to adhere to regulations and adapt their practices. Therefore, reducing incentives in Faija case might only be possible after years. Alternative actions could include adopting stricter regulatory approaches, crop substitution, or launching intensive awareness campaigns to prompt users to adapt their behavior rapidly.

The application of the ESS concept has significantly improved the understanding of human-water relationships in the MDV oases. It has helped navigate complex interactions among key variables within the MDV's SES, including social, economic, and environmental factors, providing a comprehensive view of water-related challenges and opportunities. This approach has shed light on the intricate connections between human activities and water dynamics in the MDV, such as the impact of agricultural practices on river or groundwater flow. Using the ESS approach has also highlighted the economic value of services, such as irrigation water in Chapter 3, which is crucial for sustaining livelihoods in the MDV. Testing the RCA to assess the value of this service has been valuable in understanding farmers' responses to water scarcity and drought, despite several limitations. The lack of data led to an underestimation of the value of irrigation water, as some costs were not accounted for. Furthermore, by not taking additional factors into consideration, the results were limited in their ability to fully explain all the potential reasons for farmers' decisions to dig wells, apart from decreased surface water availability. These factors could include crop selection, expansion of farming land, or other variables. Moving forward, it is essential to emphasize the importance of accurately estimating the value of irrigation water by taking all relevant factors into account for future decision-making processes.

Concerning the analytical framework used, it can be concluded that the Social-Ecological Systems Framework (SESF) is a valuable tool for structure analysis aiming to shed light on the link between water management systems in place and the broader socio-ecological contexts. It provided a starting set of variables to examine during the analysis, including potentially key variables that might need additional analysis to make complete sense of the governance process in the research area. This is precisely the case with the rules in use, which undergo an incentive structure analysis extending the utility of the SESF to understand compliance and non-compliance-related factors. This combination proved advantageous and has strengthened the analysis. However, to better understand and capture the effect of power dynamics on water management institutions, the dynamic evolution of the SESs and the impact of incentives over time require further research as mentioned above.

Throughout all chapters, securing adequate water quality and quantity emerged as a fundamental concern. Chapter 4 illustrated the direct and indirect effects of water quality on human well-being, while Chapters 3 and 5 underscored the significant impact of water availability on agricultural productivity and local livelihoods. The research indicates that one-size-fits-all governance and water allocation approaches are ineffective. Regional water policy-making in the MDV often fails to adequately consider local inhabitants' perceptions, views, and conditions. Chapters 2 and 5 emphasize the need for participatory and inclusive water management approaches, advocating for adaptive models that better reflect local social and ecological contexts. Assessing and understanding the economic value of ecosystem services (ESS) contributes by pinpointing the most critical services for livelihood maintenance and identifying the most vulnerable areas in need of urgent intervention, particularly in the context of resource scarcity, as exemplified in Chapter 3 regarding farming and farmers. This understanding is essential for designing targeted interventions, such as subsidies for water-saving technologies and equitable water allocation policies, which are necessary for supporting sustainable water management in the MDV. Appropriate incentive-based tools are needed to motivate compliance among resource users, thereby enhancing resource conservation and equitable resource use. These conclusions underscore the necessity of interdisciplinary approaches and the integration of diverse expertise for effective and sustainable solutions in the MDV's social-ecological systems (SES).

This dissertation integrates various perspectives and expertise to further advance interdisciplinary understanding, allowing for a comprehensive grasp of complex issues and practical recommendations that would not have been achievable through single-discipline research. Collaborating with ecologists in Chapter 4 offered a fresh ecological viewpoint on water quality issues within the present research. This research contributed by incorporating the human dimension to contextualize and interpret the ecological findings, through the evaluation of local perceptions regarding water quality and its impact on various livelihood aspects. Contrasting these perceptions with biophysical measurements enabled a thorough validation of our results, enhancing the credibility of our findings. Working alongside an anthropologist and social scientist in Chapter 5 led to a thorough analysis of the groundwater governance challenges and opportunities in the MDV. The social approach provided profound insights into the social and cultural contexts, which proved vital in understanding the dynamics in regions governed by customary and tribal rules, as well as the diverse categories of water users and their influence on water management and governance. This comprehension served as a fundamental foundation for the qualitative analysis of incentive adequacy, the central focus of this thesis. While the social approach highlighted the diversity of governance systems and the limitations of a uniform approach, the economic analysis of incentive structure adequacy proposes tailored governance tools based on each system's unique characteristics. This involves emphasizing incentives that discourage free-riding and align economic motivations with resource conservation goals.

Ultimately, through the recommendations outlined above, this research aspires to contribute to the ongoing discourse surrounding water ecosystem services assessment, particularly in Morocco and similar regions worldwide. This goal is to challenge the prevailing policies and practices of water management in Moroccan arid areas, which often overlook the broader significance of this essential resource. By shedding light on these limitations, the hope is to inspire more nuanced, comprehensive, and inclusive approaches to water governance, critical for defining effective management strategies.

6.3. Outlook for future research

Efforts to integrate the ESS framework into water decision-making in this arid region are crucial. While studies have been conducted on water ESS in the Drâa region, covering aspects like payment for water for drinking, irrigation, and the cinematic tourism value (Karmaoui, 2016; Zerouali et al., 2019; Karmaoui et al., 2015; Karmaoui et al., 2016; Karmaoui, 2019; Karmaoui et al., 2014; Karmaoui et al., 2020), there has been no known attempt to integrate these findings within regional water management. A future step, using the findings from this thesis, therefore involves exchanging detailed findings with concerned stakeholders and exploring ways for their potential integration into the decision-making processes in the Drâa region. The goal is to also research the best methods for the integration of knowledge, the potential challenges, and the limitations that may hinder this process. This potential future research underscores the critical need to assess the level of collaboration necessary for successful integration and raises questions about the willingness of influential actors to embrace new insights and knowledge within their decision-making. This can be done by: organizing workshops involving various stakeholders, such as local communities, water managers, and researchers which can provide a platform for collaborative dialogue, knowledge sharing, and co-creation of solutions; focus group discussions involving key stakeholders to gather diverse perspectives, identify priorities, and address potential challenges in integrating ESs findings into decision-making processes; and creating training sessions, educational programs, and knowledge-sharing initiatives for stakeholders to enhance their understanding of ESs-approaches and the role these play in decision-making, empowering stakeholders to incorporate ESs considerations into their practices.

In the MDV's palm groves, and probably similar areas around the world, micro-climate regulation facilitated by the different layers of vegetation plays an important role in creating a favorable and pleasant climate for households and making farming activities bearable amid the dry and high-temperature conditions. Demonstrating the value of this service while comparing vegetated and non-vegetated farms can also shed light on the contributions of palm trees and possibly other tree species to the livelihoods of local communities. This particular information can contribute to the promotion of sustainable agricultural practices that leverage the benefits of micro-climate regulation for improved crop yields. The valuation of micro-climate regulation can provide decision-makers with information on the tangible benefits of certain vegetation. This knowledge can inform future decisions related to land use, urban planning, and environmental conservation in the Middle Drâa Valley.

An interviewee from the MDV expressed, "If only we received a little bit more water from the dam, it might improve, and maybe we could gather next to the river like before." Water scarcity has not only impacted agricultural and domestic needs but also eroded cultural practices intrinsically tied to water resources. While the present research indicates that pressing needs for drinking water and irrigation have overshadowed cultural ecosystem services, it's crucial to examine whether this neglect stems solely from water scarcity or is compounded by current management approaches and other factors. The Mansour Eddahbi dam's pivotal role in water allocation, coupled with the diverse demands of the upper Drâa basin, such as the urban areas, golf facilities, and the Solar Station Noor for renewable energy further complicates this issue. Few studies have been conducted attempting to evaluate the flow required to maintain cultural activities in river basins under water scarcity (e.g. Lokgariwar et al., 2012; Sharma et al., 2020), but never in the MDV. Research on the water flow associated with cultural and spiritual livelihood and water is desperately needed in this water-stressed area, and quantifying this water flow may be important. Especially with the potential impacts of the new second reservoir (Agdz dam) constructed along the Drâa River. Insights from the dynamic landscape of water management in the MDV suggest that a significant shift in the perspective of water managers may be necessary. This shift involves moving beyond traditional water supply metrics to fully comprehend the vital role of cultural contributions of water resources. Comprehensive assessment and quantification of cultural water needs, and the incorporation of these values into decision-making processes, can lead towards a more holistic, sustainable, and culturally sensitive approach to water management in the MDV. This shift is fundamental not only for preserving cultural heritage but also for safeguarding community well-being and mitigating the far-reaching consequences of losing these intangible yet crucial ecosystem services.

Finally, this thesis advocates for increased interdisciplinary research to enhance our understanding of the complex interrelationships within social-ecological systems, drawing insights from diverse perspectives. Furthermore, it emphasizes the urgent need for transdisciplinary research, to facilitate the collaborative creation, effective communication, and practical integration of interdisciplinary knowledge into policymaking processes. Scientists, engineers, managers, policymakers, and stakeholders must work together to identify and formulate strategies that support ecosystem values that are often overlooked in current policy discussions.

References

Acquah, H. de Graft, and Edward Onumah. (2011). “Farmers’ Perceptions and Adaptations to Climate Change: An Estimation of Willingness to Pay.” Agris, 3(4), 31-39.

Adams, W. M., Brockington, D., Dyson, J., & Vira, B. (2003). Managing tragedies: understanding conflict over common pool resources. Science, 302(5652), 1915-1916.

Aeschbach-Hertig, W., & Gleeson, T. (2012). Regional strategies for the accelerating global problem of groundwater depletion. Nature Geoscience, 5(12), 853-861.

Akinsete, E., Apostolaki, S., Chatzistamoulou, N., Koundouri, P., Tsani, S. (2019). The Link between Ecosystem Services and Human Wellbeing in the Implementation of the European Water Framework Directive: Assessing Four River Basins in Europe. Water 11, 508. https://doi.org/10.3390/w11030508

Alcon, F., Tapsuwan, S., Brouwer, R., Yunes, M., Mounzer, O., & de-Miguel, M. D. (2019). Modeling farmer choices for water security measures in the Litani river basin in Lebanon. Science of the total environment, 647, 37-46.

Alhassan, M. (2012). Estimating farmers' willingness to pay for improved irrigation: An economic study of the Bontanga Irrigation Scheme in Northern Ghana (Doctoral dissertation, Colorado State University).

Alhassan, M., Loomis, J., Frasier, M., Davies, S., & Andales, A. (2014). An economic study of the Bontanga Irrigation Scheme in northern Ghana. Journal of Agricultural Science, 5(4), 31.

Alston, J. M., Pardey, P. G., & Roseboom, J. (1998). Financing agricultural research: international investment patterns and policy perspectives. World Development, 26(6), 1057-1071.

Al-Tawaha, A. R. M. S., Mrabet, R., Bayanati, M., Santhosh, B., Benkeblia, N., Imran, ... & Islam, S. (2022). Role of Biotechnology in Climate-Resilient Agriculture. Climate Change and Agriculture: Perspectives, Sustainability and Resilience, 78-94.

Andrews, D., & Cingano, F. (2012). Public policy and resource allocation: Evidence from firms in OECD countries. Economics Department Working Papers, No. 996; 39.

Andrews, G. J., & Duff, C. (2020). Enrolling bodies, feasting on space: How wellbeing serves the forms and flows of a new capitalism. Wellbeing, Space and Society, 1, 100004.

Archaimbault, V., Dumont, B., (2010). L’indice biologique global normalisé (IBGN): principes et évolution dans le cadre de la directive cadre européenne sur l’eau. Sciences Eaux & Territoires p-36.

Arias-Real, R., Gutiérrez-Cánovas, C., Menéndez, M., Muñoz, I. (2022). Drying niches of aquatic macroinvertebrates identify potential biomonitoring indicators in intermittent and ephemeral streams. Ecological Indicators 142, 109263. https://doi.org/10.1016/j.ecolind.2022.109263

Armitage, D. R., Plummer, R., Berkes, F., Arthur, R. I., Charles, A. T., Davidson-Hunt, I. J., ... & Wollenberg, E. K. (2009). Adaptive co-management for social-ecological complexity. Frontiers in Ecology and the Environment, 7(2), 95-102.

Arribas, P., Gutiérrez-Cánovas, C., Botella-Cruz, M., Cañedo-Argüelles, M., Antonio Carbonell, J., Millán, A., Pallarés, S., Velasco, J., Sánchez-Fernández, D. (2019). Insect communities in saline waters consist of realized but not fundamental niche specialists. Philosophical Transactions of the Royal Society B: Biological Sciences 374, 20180008. https://doi.org/10.1098/rstb.2018.0008

Arshad, M., Amjath-Babu, T. S., Kächele, H., & Müller, K. (2016). What drives the willingness to pay for crop insurance against extreme weather events (flood and drought) in Pakistan? A hypothetical market approach. Climate and Development, 8(3), 234-244.

Asprilla-Echeverria, J. (2021). The social drivers of cooperation in groundwater management and implications for sustainability. Groundwater for Sustainable Development, 15, 100668.

Assessment, M. E. (2005). Ecosystems and human well-being: wetlands and water. World Resources Institute.

Aylward, B., Bandyopadhyay, J., Belausteguigotia, J. C., Borkey, P., Cassar, A. Z., Meadors, L., ... & Bauer, C. (2005). Freshwater ecosystem services. Ecosystems and human well-being: policy responses, 3, 213-256.

Bagheri, A., & Teymouri, A. (2022). Farmers' intended and actual adoption of soil and water conservation practices. Agricultural Water Management, 259, 107244.

Baldwin, E., McCord, P., Dell'Angelo, J., & Evans, T. (2018). Collective action in a polycentric water governance system. Environmental Policy and Governance, 28(4), 212-222.

Barkley, D. L., Henry, M. S., & Kim, Y. (1999). Industry agglomerations and employment change in non-metropolitan areas. Review of urban & regional development studies, 11(3), 168-186.

Barrera-Bassols, N., & Toledo, V. M. (2005). Ethnoecology of the Yucatec Maya: symbolism, knowledge, and management of natural resources. Journal of Latin American Geography, 9-41.

Barthel, S., Folke, C., & Colding, J. (2010). Social-ecological memory in urban gardens—Retaining the capacity for management of ecosystem services. Global environmental change, 20(2), 255-265.

Bates, B., Kundzewicz, Z., & Wu, S. (2008). Climate change and water. Intergovernmental Panel on Climate Change Secretariat.

Beauchard, O., Gagneur, J., Brosse, S. (2003). Macroinvertebrate richness patterns in North African streams. Journal of Biogeography 30, 1821–1833. https://doi.org/10.1111/j.1365-2699.2003.00954.x

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific data 5, 1–12.

Benamar, L., Bennas, N., Hassoun, M., Millán, A., 2021. Threatened endemic water beetles from Morocco. J Insect Conserv 25, 465–477.

Bennett, E. M., Peterson, G. D., & Gordon, L. J. (2009). Understanding relationships among multiple ecosystem services. Ecology Letters, 12(12), 1394-1404.

Benzina, I., A. Si Bachir, C. Ghazi, F. Santoul, & R. Céréghino. (2020). How altitudinal gradient affect the diversity and composition of benthic insects in arid areas streams of northern East Algeria? Biologia 75(4): 567–577. https://doi.org/10.2478/s11756-019-00326-8

Berger, E., Bossenbroek, L., Beermann, A. J., Schäfer, R. B., Znari, M., Riethmüller, S., ... & Frör, O. (2021). Social-ecological interactions in the Drâa River Basin, southern Morocco: Towards nature conservation and human well-being using the IPBES framework. Science of the Total Environment, 769, 144492.

Berrahou, A., B. Cellot, & P. Richoux. (2001). Distribution longitudinale des macroinvertébrés benthiques de la Moulouya et de ses principaux affluents (Maroc). Annales de Limnologie - International Journal of Limnology 37(3): 223-235. https://doi.org/10.1051/limn/2001020

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., ... & West, P. C. (2012). Toward principles for enhancing the resilience of ecosystem services. Annual review of environment and resources, 37, 421-448.

Birkenholtz, T. (2014). Knowing climate change: Local social institutions and adaptation in Indian groundwater irrigation. The Professional Geographer, 66(3), 354-362.

Biswas, D., & Venkatachalam, L. (2015). Farmers' Willingness to Pay for Improved Irrigation Water—A Case Study of Malaprabha Irrigation Project in Karnataka, India. Water Economics and Policy, 1(01), 1450004.

Bockstael, N. E., Freeman, A. M., Kopp, R. J., Portney, P. R., & Smith, V. K. (2000). On measuring economic values for nature. ACS Publications. 1384-1389.

Boelens, R., & Vos, J. (2012). The danger of naturalizing water policy concepts: Water productivity and efficiency discourses from field irrigation to virtual water trade. Agricultural water management, 108, 16-26.

Bolton, G. E., & Ockenfels, A. (2000). ERC: A theory of equity, reciprocity, and competition. American Economic Review, 91(1), 166-193.

Bonada, N., S. Dolédec, & B. Statzner. (2007). Taxonomic and biological trait differences of stream macroinvertebrate communities between Mediterranean and temperate regions: implications for future climatic scenarios. Global Change Biology 13(8): 1658–1671. https://doi.org/10.1111/j.1365-2486.2007.01375.x

Borderon, M., Sakdapolrak, P., Muttarak, R., Kebede, E., Pagogna, R., & Sporer, E. (2019). Migration influenced by environmental change in Africa. Demographic Research, 41, 491-544.

Bortolini, L., Maucieri, C., & Borin, M. (2018). A tool for the evaluation of irrigation water quality in the arid and semi-arid regions. Agronomy, 8(2), 23.

Bossenbroek, L., Ftouhi, H., Kadiri, Z., & Kuper, M. (2023). Watermelons in the desert in Morocco: Struggles around a groundwater commons-in-the-making. Water Alternatives, 16(1), 87-107.

Bouchet, L., Thoms, M. C., & Parsons, M. (2019). Groundwater as a social-ecological system: A framework for managing groundwater in Pacific Small Island Developing States. Groundwater for Sustainable Development, 8, 579-589.

Bouman, B. A., Humphreys, E., Tuong, T. P., & Barker, R. (2007). Rice and water. Advances in agronomy, 92, 187-237.

Busche, H. G. K. (2013). Modeling hydrological processes in a semi-arid mountainous catchment at the regional scale (Doctoral dissertation, Universitäts-und Landesbibliothek Bonn).

Campos, M., Velázquez, A., Verdinelli, G. B., Priego-Santander, Á. G., McCall, M. K., & Boada, M. (2012). Rural people's knowledge and perception of landscape: A case study from the Mexican Pacific Coast. Society & Natural Resources, 25(8), 759-774.

Cañedo-Argüelles, M., Hawkins, C.P., Kefford, B.J., Schäfer, R.B., Dyack, B.J., Brucet, S., Buchwalter, D., Dunlop, J., Frör, O., Lazorchak, J. (2016). Saving freshwater from salts. Science 351, 914–916.

Capon, S. J., Chambers, L. E., Mac Nally, R., Naiman, R. J., Davies, P., Marshall, N., ... & Williams, S. E. (2013). Riparian ecosystems in the 21st century: hotspots for climate change adaptation? Ecosystems, 16, 359-381.

Carrillo-Rivera, J. J., Ouysse, S., & Hernández-Garcia, G. J. (2013). Integrative approach for studying water sources and their vulnerability to climate change in semi-arid regions (Drâa Basin, Morocco). International Journal of Water Resources and Arid Environments, 3(1), 26-36.

Castro, J. E. (2007). Water governance in the twenty-first century. Ambiente & Sociedad, 10, 97-118.

Cavender-Bares, J., Balvanera, P., King, E., & Polasky, S. (2015). Ecosystem service trade-offs across global contexts and scales. Ecology and Society, 20(1).

CHANGE, O. C. (2007). Intergovernmental panel on climate change. World Meteorological Organization, 52, 1-43.

Chen, J., Yin, S., Gebhardt, H., & Yang, X. (2018). Farmers' livelihood adaptation to environmental change in an arid region: A case study of the Minqin Oasis, northwestern China. Ecological indicators, 93, 411-423.

Cherkaoui, H. D., Moussadek, R., & Sahbi, H. (2007). Apport des techniques géospatiales pour la caractérisation de la qualité des eaux sous-terraines des oasis de la vallée du Draa-cas de la nappe de Fezouata. Options Méditerranéennes : Série B. Etudes et Recherches, 2(56), 295.

Clarke, J.U. (1998). Evaluation of Censored Data Methods to Allow Statistical Comparisons among Very Small Samples with Below Detection Limit Observations. Environ. Sci. Technol. 32, 177–183. https://doi.org/10.1021/es970521v

Clavero, M., Esquivias, J., Qninba, A., Riesco, M., Calzada, J., Ribeiro, F., Fernández, N., Delibes, M. (2015). Fish invading deserts: non-native species in arid Moroccan rivers. Aquatic Conservation: Marine and Freshwater Ecosystems 25, 49–60. https://doi.org/10.1002/aqc.2487

Cleaver, F. (1999). Paradoxes of participation: question ing participatory approaches to development. Journal of International Development: The Journal of the Development Studies Association, 11(4), 597-612.

Cleaver, F. (2000). Moral ecological rationality, institutions and the management of common property resources. Development and change, 31(2), 361-383.

Closas, A., & Villholth, K. G. (2016). Aquifer contracts: a means to solving groundwater over-exploitation in Morocco? (Vol. 1). International Water Management Institute (IWMI).

Closas, A., & Villholth, K. G. (2020). Groundwater governance: Addressing core concepts and challenges. Wiley Interdisciplinary Reviews: Water, 7(1), e1392.

Cody, C., Ford, V., & Siraj, A. (2015). Decision tree learning for fraud detection in consumer energy consumption. In 2015 IEEE 14th international conference on machine learning and applications (ICMLA) (pp. 1175-1179). IEEE.

Costanza, R., De Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., ... & Grasso, M. (2017). Twenty years of ecosystem services: How far have we come and how far do we still need to go? Ecosystem services, 28, 1-16.

Costanza, R., Pérez-Maqueo, O., Martinez, M. L., Sutton, P., Anderson, S. J., & Mulder, K. (2008). The value of coastal wetlands for hurricane protection. Ambio, 241-248.

Covich, A.P., Palmer, M.A., Crowl, T.A. (1999). The role of benthic invertebrate species in freshwater ecosystems: zoobenthic species influence energy flows and nutrient cycling. BioScience 49, 119–127.

Cox, M., Arnold, G., & Tomás, S. V. (2010). A review of design principles for community-based natural resource management. Ecology and Society, 15(4).

Cruz-Garcia, G.S., Sachet, E., Blundo-Canto, G., Vanegas, M., Quintero, M. (2017). To what extent have the links between ecosystem services and human well-being been researched in Africa, Asia, and Latin America? Ecosystem Services 25, 201–212. https://doi.org/10.1016/j.ecoser.2017.04.005

Cullet, P. (2006). Water law reforms-analysis of recent developments. Journal of the Indian law Institute, 48(2), 206-231.

Cundill, G., & Fabricius, C. (2009). Monitoring in adaptive co-management: toward a learning-based approach. Journal of Environmental Management, 90(11), 3205-3211.

Cunillera-Montcusí, D., Beklioğlu, M., Cañedo-Argüelles, M., Jeppesen, E., Ptacnik, R., Amorim, C.A., Arnott, S.E., Berger, S.A., Brucet, S., Dugan, H.A. (2022). Freshwater salinisation: a research agenda for a saltier world. Trends in Ecology & Evolution.

Daily, G. C. (1997). Introduction: what are ecosystem services? Nature's services: Societal dependence on natural ecosystems, 1(1).

Delmas, M. A., & Montes-Sancho, M. J. (2010). Voluntary agreements to improve environmental quality: Symbolic and substantive cooperation. Strategic Management Journal, 31(6), 575-601.

Delmas, M., & Keller, A. (2005). Free riding in voluntary environmental programs: The case of the US EPA Waste Wise program. Policy Sciences, 38(2), 91-106.

Dessu, S.B., Melesse, A.M., Bhat, M.G., McClain, M.E. (2014). Assessment of water resources availability and demand in the Mara River Basin. Catena 115, 104–114.

Diekkruger, B., Busche, H. E. N. N. I. N. G., Klose, A. N. N. A., Klose, S. T. E. P. H. A. N., Rademacher, C. H. R. I. S. T. I. N. A., & Schulz, O. L. I. V. E. R. (2010). Impact of global change on hydrology and soil degradation–scenario analysis for the semi-arid Drâa catchment (South Morocco). The global dimension of change in river basins: Threat, linkages and adaptation, 5-13.

Dolisca, F., McDaniel, J. M., & Teeter, L. D. (2007). Farmers' perceptions towards forests: A case study from Haiti. Forest Policy and Economics, 9(6), 704-712.

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., McClean, C., Osborne, P.E., Reineking, B., Schröder, B., Skidmore, A.K., Zurell, D., Lautenbach, S. (2013). Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography 36, 27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x

Edegbene, A.O., Elakhame, L.A., Arimoro, F.O., Osimen, E.C., Odume, O.N. (2019). Development of macroinvertebrate multimetric index for ecological evaluation of a river in North Central Nigeria. Environ Monit Assess 191, 274. https://doi.org/10.1007/s10661-019-7438-8

El Moçayd, N., Kang, S., Eltahir, E.A.B. (2020). Climate change impacts on the Water Highway project in Morocco. Hydrology and Earth System Sciences 24, 1467–1483. https://doi.org/10.5194/hess-24-1467-2020

El Mokhtar, M. A., Laouane, R. B., Anli, M., Boutasknit, A., Fakhech, A., Wahbi, S., & Meddich, A. (2022). Climate change and its impacts on oases ecosystem in Morocco. In Research Anthology on Environmental and Societal Impacts of Climate Change (pp. 1103-1131). IGI Global.

Elwell, T. L., Gelcich, S., Gaines, S. D., & López-Carr, D. (2018). Using people's perceptions of ecosystem services to guide modeling and management efforts. Science of the Total Environment, 637, 1014-1025.

Ernstson, H. (2013). The social production of ecosystem services: A framework for studying environmental justice and ecological complexity in urbanized landscapes. Landscape and urban planning, 109(1), 7-17.

Esguerra, A., Beck, S., & Lidskog, R. (2017). Stakeholder engagement in the making: IPBES legitimization politics. *Global Environmental Politics*, *17*(1), 59-76.

Euler, J., & Heldt, S. (2018). From information to participation and self-organization: Visions for European river basin management. Science of the Total Environment, 621, 905-914.

Fagerholm, N., Käyhkö, N., Ndumbaro, F., & Khamis, M. (2012). Community stakeholders' knowledge in landscape assessments–Mapping indicators for landscape services. Ecological Indicators, 18, 421-433.

Fan, Y., Tang, Z., & Park, S. C. (2019). Effects of community perceptions and institutional capacity on smallholder farmers' responses to water scarcity: Evidence from arid northwestern China. Sustainability, 11(2), 483.

Feio, M.J., Hughes, R.M., Callisto, M., Nichols, S.J., Odume, O.N., Quintella, B.R., Kuemmerlen, M., Aguiar, F.C., Almeida, S.F.P., Alonso-EguíaLis, P., Arimoro, F.O., Dyer, F.J., Harding, J.S., Jang, S., Kaufmann, P.R., Lee, S., Li, J., Macedo, D.R., Mendes, A., Mercado-Silva, N., Monk, W., Nakamura, K., Ndiritu, G.G., Ogden, R., Peat, M., Reynoldson, T.B., Rios-Touma, B., Segurado, P., Yates, A.G. (2021). The Biological Assessment and Rehabilitation of the World's Rivers: An Overview. Water 13, 371. https://doi.org/10.3390/w13030371

Ferreira, V., Albariño, R., Larrañaga, A., LeRoy, C.J., Masese, F.O., Moretti, M.S. (2022). Ecosystem services provided by small streams: an overview. Hydrobiologia. https://doi.org/10.1007/s10750-022-05095-1

Fienen, M. N., & Arshad, M. (2016). The international scale of the groundwater issue. Integrated groundwater management: concepts, approaches and challenges, 21-48.

Folke, C., Biggs, R., Norström, A. V., Reyers, B., & Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. Ecology and Society, 21(3).

Fox, J., Friendly, G.G., Graves, S., Heiberger, R., Monette, G., Nilsson, H., Ripley, B., Weisberg, S., Fox, M.J., Suggests, M. (2007). The car package. R Foundation for Statistical Computing 1109.

Frumkin, H., Bratman, G.N., Breslow, S.J., Cochran, B., Kahn Jr, P.H., Lawler, J.J., Levin, P.S., Tandon, P.S., Varanasi, U., Wolf, K.L., Wood, S.A. (2017). Nature Contact and Human Health: A Research Agenda. Environ Health Perspect 125, 075001. https://doi.org/10.1289/EHP1663

Gardner, R., Moore, M. R., & Walker, J. M. (1997). Governing a groundwater common: a strategic and laboratory analysis of western water law. Economic Inquiry, 35(2), 218-234.

Gebretsadik, K. A., & Romstad, E. (2020). Climate and farmers' willingness to pay for improved irrigation water supply. World Development Perspectives, 20, 100233.

Gergen, K. J. (2016). Toward a visionary psychology. The Humanistic Psychologist, 44(1), 3.

Gergen, K.J. (2009). Relational being: Beyond self and community. Oxford University Press.

Ghosh, R., & Kansal, A. (2019). Anthropology of changing paradigms of urban water systems. Water History, 11(1), 59-73.

Ghougali, F., A. S. Bachir, N. Chaabane, I. Brik, R. A. Medjber, & A. Rouabah. (2019). Diversity and distribution patterns of benthic insects in streams of the Aurès arid region (NE Algeria). Oceanological and Hydrobiological Studies 48(1): 31–42. https://doi.org/10.1515/ohs-2019-0004

Giudicelli, J., & M. Dakki, 1984. Les Sources du Moyen Atlas et de Rif (Maroc): Faunistique (Description de Deux Espèces Nouvelles de Trichoptères), Écologie, Intérêt Biogéographique. Bijdragen tot de Dierkunde 54(1): 83–100.

Gneezy, U., Meier, S., & Rey-Biel, P. (2011). When and why incentives (don't) work to modify behavior. Journal of economic perspectives, 25(4), 191-210.

Gorelick, S. M., & Zheng, C. (2015). Global change and the groundwater management challenge. Water Resources Research, 51(5), 3031-3051.

Greiby, I. E., & Fennir, M. A. (2023). Postharvest Handling of Dates. In Date Palm (pp. 454-485). GB: CABI.

Greiner, R., Fernandes, L., McCartney, F., & Durante, J. (2016). Reasons why some irrigation water users fail to comply with water use regulations: A case study from Queensland, Australia. Land Use Policy, 51, 26-40.

Guerbois, C., & Fritz, H. (2017). Patterns and perceived sustainability of provisioning ecosystem services on the edge of a protected area in times of crisis. Ecosystem services, 28, 196-206.

Guerry, A. D., Polasky, S., Lubchenco, J., Chaplin-Kramer, R., Daily, G. C., Griffin, R., ... & Vira, B. (2015). Natural capital and ecosystem services informing decisions: From promise to practice. Proceedings of the National Academy of Sciences, 112(24), 7348-7355.

Gutiérrez-Cánovas, C., Arribas, P., Naselli-Flores, L., Bennas, N., Finocchiaro, M., Millán, A., Velasco, J. (2019). Evaluating anthropogenic impacts on naturally stressed ecosystems: Revisiting river classifications and biomonitoring metrics along salinity gradients. Science of The Total Environment 658, 912–921. https://doi.org/10.1016/j.scitotenv.2018.12.253

Gutierrez-Cánovas, C., Velasco García, J., Millán Sánchez, A. (2008). SALINDEX: A macroinvertebrate index for assessing the ecological status of saline “ramblas” from SE of the Iberian Peninsula. Limnetica 27, 299–316. https://doi.org/10.23818/limn.27.24

Haines-Young, R., & Potschin, M. (2010). The links between biodiversity, ecosystem services, and human well-being. Ecosystem Ecology: a new synthesis, 1, 110-139.

Haines-Young, R., & Potschin, M. (2012). Common international classification of ecosystem services (CICES, Version 4.1). European Environment Agency, 33, 107.

Haj-Amor, Z., Ibrahimi, M.-K., Feki, N., Lhomme, J.-P., Bouri, S. (2016). Soil salinization and irrigation management of date palms in a Saharan environment. Environmental monitoring and assessment 188, 1–17.

Han, Z., Huang, S., Huang, Q., Leng, G., Wang, H., Bai, Q., ... & Du, M. (2019). Propagation dynamics from meteorological to groundwater drought and their possible influence factors. Journal of Hydrology, 578, 124102.

Hartig, T., Mitchell, R., De Vries, S., Frumkin, H. (2014). Nature and health. Annual review of public health 35, 207–228.

Hartter, J. (2010). Resource use and ecosystem services in a forest park landscape. Society and Natural Resources, 23(3), 207-223.

HCP—Haut-Commissariat au Plan Direction Régionale d’Errachidia (2015). Annuaire Statistique Regional Draa-Tafilalet. Available online: https://www.hcp.ma/draatafilalet/attachment/998567/ (accessed on 10 April 2021).

Heidecke, C. (2010). Economic analysis of water use and management in the Middle Drâa Valley in Morocco (Doctoral dissertation, Universitäts-und Landesbibliothek Bonn).

Heidecke, C. and Schmidt, T. (2008). Agricultural Land Use. Impetus Atlas Morocco: research results, 67-68. 3., Major Rev. Ed. Bonn: University of Bonn, Department of Geography.

Hein, L., Van Koppen, K., De Groot, R. S., & Van Ierland, E. C. (2006). Spatial scales, stakeholders, and the valuation of ecosystem services. Ecological economics, 57(2), 209-228.

Helsel, D. (2010). Much Ado About Next to Nothing: Incorporating Nondetects in Science. The Annals of Occupational Hygiene 54, 257–262. https://doi.org/10.1093/annhyg/mep092Hssaisoune, M., Bouchaou, L., Sifeddine, A., Bouimetarhan, I., Chehbouni, A., 2020. Moroccan groundwater resources and evolution with global climate changes. Geosciences 10, 81.

Helsel, D.R. (2006). Fabricating data: How substituting values for nondetects can ruin results, and what can be done about it. Chemosphere, Environmental Chemistry 65, 2434–2439. https://doi.org/10.1016/j.chemosphere.2006.04.051

Hinchi, I., Bouayad, K., Fadil, F. (2020). Hydrobiological study of the source Tadout (Middle Atlas, Morocco): Physical chemistry, microbiology, and benthic fauna. Global Scientific Journals 8(1), 1451-1473.

Holley, C., & Sinclair, D. (2012). Compliance and enforcement of water licenses in NSW: limitations in law, policy, and institutions. Australasian Journal of Natural Resources Law and Policy, 15(2), 149-189.

Holt, T., Greskowiak, J., Sültenfuß, J., & Massmann, G. (2021). Groundwater age distribution in a highly dynamic coastal aquifer. Advances in Water Resources, 149, 103850.

Houdret, A. (2012). The water connection: Irrigation, water grabbing and politics in southern Morocco. Houdret, A, 284-303.

Houdret, A., & Heinz, R. (2023). Groundwater governance through institutional bricolage? Participation in Morocco's Chtouka aquifer contract. In Groundwater (pp. 59-76). Routledge.

Howarth, R. B., Haddad, B. M., & Paton, B. (2000). The economics of energy efficiency: insights from voluntary participation programs. Energy policy, 28(6-7), 477-486.

Hssaisoune, M., Bouchaou, L., Sifeddine, A., Bouimetarhan, I., & Chehbouni, A. (2020). Moroccan groundwater resources and evolution with global climate changes. Geosciences (Switzerland), 10 (2).

Huggins, X., Gleeson, T., Castilla-Rho, J., Holley, C., Re, V., & Famiglietti, J. S. (2023). Groundwater connections and sustainability in social-ecological systems. Groundwater, 61(4), 463-478.

Huntsinger, L., & Oviedo, J. L. (2014). Ecosystem services are social–ecological services in a traditional pastoral system: The case of California's Mediterranean rangelands. Ecology and Society, 19(1).

Iftekhar, M. S., & Takama, T. (2008). Perceptions of biodiversity, environmental services, and conservation of planted mangroves: a case study on Nijhum Dwip Island, Bangladesh. Wetlands Ecology and Management, 16, 119-137.

Ingram, J. (2011). A food systems approach to researching food security and its interactions with global environmental change. Food security, 3, 417-431.

Iniguez-Gallardo, V., Halasa, Z., Briceño, J., & Iniguez-Gallardo, V. (2018). People's perceptions of ecosystem services provided by tropical dry forests: A comparative case study in Southern Ecuador. Tropical Forests—New Edition; IntechOpen: London, UK, 5, 95-113.

Jáimez-Cuéllar, P., Vivas, S., Bonada, N., Robles, S., Mellado, A., Álvarez, M., Avilés, J., Casas, J., Ortega, M., Pardo, I. (2002). Protocolo GUADALMED (prece). Limnetica 21, 187–204.

Jakubínský, J., Prokopová, M., Raška, P., Salvati, L., Bezak, N., Cudlín, O., Cudlín, P., Purkyt, J., Vezza, P., Camporeale, C., Daněk, J., Pástor, M., Lepeška, T. (2021). Managing floodplains using nature-based solutions to support multiple ecosystem functions and services. WIREs Water 8, e1545. https://doi.org/10.1002/wat2.1545

Jeddi, T.A., Hssaisoune, M., Saad, A., El Morjani, Z.E.A., Mazziz, M., Beraaouz, M., BOUCHAOU, L. (2021). Water resources status to global changes in the Taznakht plain, Draa basin, Morocco. Frontiers in Science and Engineering 11.

Jentoft, S., van Son, T. C., & Bjørkan, M. (2007). Marine protected areas: a governance system analysis. Human ecology, 35, 611-622.

Jentsch, A., & Beierkuhnlein, C. (2008). Research frontiers in climate change: effects of extreme meteorological events on ecosystems. Comptes Rendus Geoscience, 340(9-10), 621-628.

Johannsen, I. M., Hengst, J. C., Goll, A., Höllermann, B., & Diekkrüger, B. (2016). Future of water supply and demand in the Middle Drâa Valley, Morocco, under climate and land use change. Water, 8(8), 313.

Johannsen, I.M., Hengst, J.C., Goll, A., Höllermann, B., Diekkrüger, B. (2016). Future of water supply and demand in the Middle Drâa Valley, Morocco, under climate and land use change. Water 8, 313.

Jones, B.A. (2017). Invasive Species Impacts on Human Well-being Using the Life Satisfaction Index. Ecological Economics 134, 250–257. https://doi.org/10.1016/j.ecolecon.2017.01.002

Kaczmarek, N., Schaefer, R.B., Berger, E. (2021). Environmental Change Threatens Freshwater Insect Communities in Northwest Africa: A Meta-Analysis. Frontiers in Environmental Science 302.

Kadiri, Z., Kuper, M., Faysse, N., & Errahj, M. (2009). Local transformation of a state-initiated institutional innovation: The example of water users' associations in an irrigation scheme in Morocco. Irrigation and drainage, 58(S3), S346-S357.

Kals, E., Maes, J. (2002). Sustainable development and emotions, in Psychology of Sustainable Development. Springer, pp. 97–122.

Kampstra, P., 2008. Beanplot: A boxplot alternative for visual comparison of distributions. Journal of Statistical Software 28, 1–9.

Kaplan, R. (2001). The nature of the view from home: Psychological benefits. Environment and behavior 33, 507–542.

Karmaoui, A. (2019). Drought and desertification in Moroccan Pre-Sahara, Draa valleys: exploring from the perspective of young people. Geoenvironmental Disasters, 6, 1-13.

Karmaoui, A., Ifaadassan, I., Messouli, M., & Khebiza, M. Y. (2015). Characterization of common environmental indicators of the Moroccan Oasean Biome, Pilot study in the reserve biosphere of Oases in Southern Morocco. Advances in Research, 5(5), 1-15.

Karmaoui, A., Messouli, M., Khebiza, M. Y., & Ifaadassan, I. (2014). Environmental vulnerability to climate change and anthropogenic impacts in dryland, (pilot study: Middle Draa Valley, South Morocco). Journal of Earth Science & Climatic Change, 5(Special Issue).

Karmaoui, A., Zerouali, S., Shah, A. A., Yacoubi-Khebiza, M., & El Qorchi, F. (2019). Ecosystem services-climate-health associations: water-climate-Leishmaniasis Nexus in an endemic focus of zoonotic Cutaneous Leishmaniasis. In Climate Change and Its Impact on Ecosystem Services and Biodiversity in Arid and Semi-Arid Zones (pp. 280-290). IGI Global.

Karrouch, L., A. Chahlaoui, & A. Essahale. (2017). Anthropogenic impacts on the distribution and biodiversity of benthic macroinvertebrates and water quality of the Boufekrane River, Meknes, Morocco. Journal of Geoscience and Environment Protection 5(07): 173. https://doi.org/10.4236/gep.2017.57014

Kassambara, A. (2020). rstatix: Pipe-friendly framework for basic statistical tests. R package version 0.6. 0.

Keesing, F., Ostfeld, R.S. (2021). Impacts of biodiversity and biodiversity loss on zoonotic diseases. Proceedings of the National Academy of Sciences 118, e2023540118. https://doi.org/10.1073/pnas.2023540118

Kefford, B.J., Buchwalter, D., Cañedo-Argüelles, M., Davis, J., Duncan, R.P., Hoffmann, A., Thompson, R. (2016). Salinized rivers: degraded systems or new habitats for salt-tolerant faunas? Biology Letters 12, 20151072.

Kerr, J., Vardhan, M., & Jindal, R. (2012). Prosocial behavior and incentives: evidence from field experiments in rural Mexico and Tanzania. Ecological Economics, 73, 220-227.

Kevin, W. (2014). Africa Progress Report 2014: Grain, Fish, Money: Financing Africa's Green and Blue Revolutions. Geneva: Africa Progress Panel.

Khebiza, M. Y., A. A. Boughrous, C. Gabbanini, M. Messouli, & G. Messana. (2006). Impact of waste discharges on the water quality and interstitial community structure of two Mediterranean rivers. Italian Journal of Zoology 73(2): 153–166. https://doi.org/10.1080/11250000600679462

Kingdon, J. W. (1995). Agendas, alternatives, and public policies. 2nd. NY: HarperCollins College Publisher.

Kiprop, J., Mulungu, K., Kibet, N., & Macharia, A. (2017). Determinants of smallholder farmers' willingness to pay for irrigation water in Kerio Valley Basin, Kenya.

Klose, A. (2009). Soil characteristics and soil erosion by water in a semi-arid catchment (Wadi Drâa, South Morocco) under the pressure of global change (Doctoral dissertation, Universitäts-und Landesbibliothek Bonn).

Klose, S., Busche, H., Klose, A., Schulz, O., Diekkrüger, B., Reichert, B., & Winiger, M. (2010). Impacts of global change on water resources and soil salinity in Southern Morocco. SPETH P., M. CHRISTOPH & B. DIEKKRÜGER: Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer Heidelberg, DOI, 10(9783642129575), 592-610.

Klose, S., Reichert, B., & Lahmouri, A. (2008). Management options for sustainable groundwater use in the Middle Drâa Oases under the pressure of climatic changes. In Climatic changes and water resources in the Middle East and North Africa (pp. 179-195). Berlin, Heidelberg: Springer Berlin Heidelberg.

Kooiman, J. (2003). Societal governance (pp. 229-250). VS Verlag für Sozialwissenschaften.

Kooiman, J. (2016). Interactive governance and governability. In Critical reflections on interactive governance (pp. 29-50). Edward Elgar Publishing.

Kooiman, J., & Van Vliet, M. (2000). Self-governance as a mode of societal governance. Public management an international journal of research and theory, 2(3), 359-378.

Kuhn, M. (2009). The caret package. Journal of Statistical Software 28.

Krug, C. B., Sterling, E., Cadman, T., Geschke, J., Drummond de Castro, P. F., Schliep, R., ... & Maraseni, T. (2020). Stakeholder participation in IPBES: connecting local environmental work with global decision making. *Ecosystems and People*, *16*(1), 197-211.

Kuper, M., Faysse, N., Hammani, A., Hartani, T., Marlet, S., Hamamouche, M. F., & Ameur, F. (2016). Liberation or anarchy? The Janus nature of groundwater use on North Africa's new irrigation frontiers. Integrated groundwater management: Concepts, approaches and challenges, 583-615.

Kuper, M., Leduc, C., Massuel, S., & Bouarfa, S. (2017). Topical Collection: Groundwater-based agriculture in the Mediterranean. Hydrogeology Journal, 25(6), 1525.

Lamqadem, A. A., Afrasinei, G. M., & Saber, H. (2019). Analysis of Landsat-derived multitemporal vegetation cover to understand drivers of oasis agroecosystems change. Journal of Applied Remote Sensing, 13(1), 014517-014517.

Lapar, M. L. A., Toan, N. N., Staal, S., Minot, N., Tisdell, C., Que, N. N., & Tuan, N. D. A. (2018). Smallholder competitiveness: insights from household pig production systems in Vietnam. International Association of Agricultural Economists Conference, Foz Do Iguaçu, Brazil.

Larsen, G.M. (2012). Wetland and Lake Destruction, Development, and Mental/Emotional Distress Among Residents of Tampa Bay, Florida. University of South Florida.

Lecerf, A., Richardson, J.S. (2010). Biodiversity-ecosystem function research: Insights gained from streams. River Research and Applications 26, 45–54. https://doi.org/10.1002/rra.1286

Leschine, T. M., Wellman, K. F., & Green, T. H. (1997). The economic value of wetlands: wetlands' role in flood protection in Western Washington. Washington State Department of Ecology.

Lewis, S. L., & Maslin, M. A. (2015). Defining the Anthropocene. Nature, 519(7542), 171-180.

Lezzaik, K., Milewski, A., & Mullen, J. (2018). The groundwater risk index: Development and application in the Middle East and North Africa region. Science of the Total Environment, 628, 1149-1164.

Liu, M., Wei, H., Dong, X., Wang, X.-C., Zhao, B., Zhang, Y. (2022). Integrating Land Use, Ecosystem Service, and Human Well-Being: A Systematic Review. Sustainability 14, 6926.

López-Morales, C. A., & Mesa-Jurado, M. A. (2017). Valuation of hidden water ecosystem services: the replacement cost of the aquifer system in Central Mexico. Water, 9(8), 571.

López-Rodríguez, M. D., Cabello, J., Castro, H., & Rodríguez, J. (2019). Social learning for facilitating dialogue and understanding of the ecosystem services approach: lessons from a cross-border experience in the Alboran Marine Basin. Sustainability, 11(19), 5239.

Maamri, A., E. Pattee, S. Dolédec, & H. Chergui. (2005). The benthic macroinvertebrate assemblages in the Zegzel-Cherraa, a partly-temporary river system, Eastern Morocco. Annales de Limnologie - International Journal of Limnology 41(4): 247–257. https://doi.org/10.1051/limn/2005017

Maarleveld, M., & Dabgbégnon, C. (1999). Managing natural resources: A social learning perspective. Agriculture and human values, 16, 267-280.

Mabrouki, Y., A. F. Taybi, M. El Alami, & A. Berrahou. (2019). Biotypology of stream macroinvertebrates from North African and semi-arid catchment: Oued Za (Morocco). Knowledge & Management of Aquatic Ecosystems 420: 17. https://doi.org/10.1051/kmae/2019009

Mace, G.M. (2014). Whose conservation? Science 345, 1558–1560.

Mafoua, E. (2002). Economies of Scope and Scale of Multi-Product US Cash Grain Farms: A Flexible Fixed-Cost Quadratic (FFCQ) Model Analysis.

Mahjoubi, I., Bossenbroek, L., Berger, E., & Frör, O. (2022). Analyzing Stakeholder Perceptions of Water Ecosystem Services to Enhance Resilience in the Middle Drâa Valley, Southern Morocco. Sustainability, 14(8), 4765.

Mahmoudi, A. S., Al-Barrak, K. M., & Massoud, M. A. (2011). 2-D electrical tomography for mapping of aquifers at the new campus of King Faisal University, Al Hassa, KSA. International Journal of Water Resources and Arid Environments, 1(6), 397-410.

Maltby, E., Ormerod, S., Acreman, M., Dunbar, M., Jenkins, A., Maberly, S., ... & Ward, R. (2011). Freshwaters: openwaters, wetlands, and floodplains [chapter 9].

Marselle, M.R., Martens, D., Dallimer, M., Irvine, K.N. (2019). Review of the mental health and well-being benefits of biodiversity, in Biodiversity and Health in the Face of Climate Change. Springer, Cham, pp. 175–211.

Martin, S. (2011). Influence du tourisme sur la gestion de l'eau en zone aride : exemple de la vallée du Drâa, Maroc. Editions universitaires européennes.

Martín-López, B., Iniesta-Arandia, I., García-Llorente, M., Palomo, I., Casado-Arzuaga, I., Amo, D. G. D., ... & Montes, C. (2012). Uncovering ecosystem service bundles through social preferences. PLoS one, 7(6), e38970.

Martin-Ortega, J., Ferrier, R. C., Gordon, I. J., & Khan, S. (2015). Water ecosystem services: a global perspective. UNESCO Publishing.

Mason, M. (2010, August). Sample size and saturation in PhD studies using qualitative interviews. In Forum qualitative Sozialforschung/Forum: qualitative social research (Vol. 11, No. 3).

McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. Ecology and society, 19(2).

McShane, T. O., Hirsch, P. D., Trung, T. C., Songorwa, A. N., Kinzig, A., Monteferri, B., ... & O'Connor, S. (2011). Hard choices: Making trade-offs between biodiversity conservation and human well-being. Biological conservation, 144(3), 966-972.

Mehta, V. K., Young, C., Bresney, S. R., Spivak, D. S., & Winter, J. M. (2018). How can we support the development of robust groundwater sustainability plans? California Agriculture, 72(1).

Messager, M.L., Lehner, B., Cockburn, C., Lamouroux, N., Pella, H., Snelder, T., Tockner, K., Trautmann, T., Watt, C., Datry, T. (2021). Global prevalence of non-perennial rivers and streams. Nature 594, 391–397. https://doi.org/10.1038/s41586-021-03565-5

Michetti, M., Raggi, M., Guerra, E., & Viaggi, D. (2019). Interpreting farmers' perceptions of risks and benefits concerning wastewater reuse for irrigation: a case study in Emilia-Romagna (Italy). Water, 11(1), 108.

Minehart, D., & Neeman, Z. (1999). Termination and coordination in partnerships. Journal of Economics & Management Strategy, 8(2), 191-221.

Mitra, S., Mehta, P. K., & Mishra, S. K. (2021). Farmers' perception, adaptation to groundwater salinity, and climate change vulnerability: Insights from North India. Weather, Climate, and Society, 13(4), 797-811.

Moher, D., A. Liberati, J. Tetzlaff, D. G. Altman. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Annals of internal medicine, 151(4): 264-269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135

Molle, F. (2008). Nirvana concepts, narratives, and policy models: Insights from the water sector. Water Alternatives, 1(1), 131-156.

Molle, F., & Closas, A. (2020). Comanagement of groundwater: A review. Wiley Interdisciplinary Reviews: Water, 7(1), e1394.

Molle, F., & Tanouti, O. (2017). Squaring the circle: Agricultural intensification vs. water conservation in Morocco. Agricultural water management, 192, 170-179.

Mooney, H. A., Ehrlich, P. R., & Daily, G. E. (1997). Ecosystem services: a fragmentary history. Nature's services: Societal dependence on natural ecosystems, 1, 11-19.

Mostakim, L., Guennoun, F.Z., Benaissa, H., Fetnassi, N., Ghamizi, M. (2022). EFFECTS OF LAND USE CHANGE ON THE RIPARIAN ZONES' QUALITY ALONG THE ZAT RIVER AND ITS TRIBUTARIES: HIGH ATLAS OF MOROCCO. Appl. Ecol. Env. Res. 20, 1351–1367. https://doi.org/10.15666/aeer/2002_13511367

Moumane, A., El Ghazali, F. E., Al Karkouri, J., Delorme, J., Batchi, M., Chafiki, D., & Karmaoui, A. (2021). Monitoring spatiotemporal variation of groundwater level and salinity under land use change using integrated field measurements, GIS, geostatistical, and remote-sensing approach: a case study of the Feija aquifer, Middle Draa watershed, Moroccan Sahara. Environmental Monitoring and Assessment, 193, 1-21.

Muhamad, D., Okubo, S., Harashina, K., Gunawan, B., & Takeuchi, K. (2014). Living close to forests enhances people's perception of ecosystem services in a forest–agricultural landscape of West Java, Indonesia. Ecosystem Services, 8, 197-206.

Muñoz-Arriola, F., Abdel-Monem, T., & Amaranto, A. (2021). Common pool resource management: assessing water resources planning for hydrologically connected surface and groundwater systems. Hydrology, 8(1), 51.

Muñoz-Arriola, F., Abdel-Monem, T., & Amaranto, A. (2021). Common pool resource management: assessing water resources planning for hydrologically connected surface and groundwater systems. Hydrology, 8(1), 51.

Navarro, H., & Navarro, S. (2015). Post-harvest processing of dates: drying, disinfestation, and storage. Sustainable Pest Management in Date Palm: Current Status and Emerging Challenges, 391-409.

Nechad, I., & F. Fadil. (2016). Taxonomic diversity of benthic stands of the Tataw source (Imouzer Marmoucha, Middle Atlas - Morocco). IJSER 7: 17.

Nicolás-Ruiz, N., Suárez Alonso, M.L., Vidal-Abarca, M.R. (2021). Contributions of dry rivers to human well-being: A global review for future research. Ecosystem Services 50, 101307. https://doi.org/10.1016/j.ecoser.2021.101307

Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. American Economic Review, 105(4), 1339-1370.

O'Connor, C., & Joffe, H. (2020). Intercoder reliability in qualitative research: debates and practical guidelines. International journal of qualitative methods, 19, 1609406919899220.

OECD. (2011). Water governance in OECD countries: A multi-level approach. OECD.

Olivier de Sardan, J. P., De Herdt, T., & Olivier de Sardan, J. P. (2015). Real Governance and Practical Norms in Sub-Saharan Africa: the game of the rules.

Ostrom, E. (1990). Governing the commons: The evolution of institutions for collective action. Cambridge University Press.

Ostrom, E. (1992). Community and the endogenous solution of commons problems. Journal of theoretical politics, 4(3), 343-351.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. Science, 325(5939), 419-422.

Ostrovskaya, E., Douven, W., Schwartz, K., Pataki, B., Mukuyu, P., & Kaggwa, R. C. (2013). Capacity for sustainable management of wetlands: Lessons from the WETwin project. Environmental science & policy, 34, 128-137.

Ouhajou, L. (1996). Espace hydraulique et société au Maroc : cas des systèmes d'irrigation dans la vallée du Draa.

Ou-Zine, M., Symanczik, S., Rachidi, F., Fagroud, M., Aziz, L., Abidar, A., Mäder, P., Achbani, E.H., Haggoud, A., Abdellaoui, M., Bouamri, R. (2021). Effect of Organic Amendment on Soil Fertility, Mineral Nutrition, and Yield of Majhoul Date Palm Cultivar in Drâa-Tafilalet Region, Morocco. J Soil Sci Plant Nutr 21, 1745–1758. https://doi.org/10.1007/s42729-021-00476-2

Pagiola, S., Agostini, P., Gobbi, J., de Haan, C., Ibrahim, M., Murgueitio, E., ... & Ruíz, J. P. (2004). Pago por servicios de conservación de la biodiversidad en paisajes agropecuarios. World Bank. Washington, US.

Pagiola, S., Von Ritter, K., & Bishop, J. (2004). Assessing the economic value of ecosystem conservation.

Pahl-Wostl, C. (2015). Water governance in the face of global change. Switzerland: Springer.

Pahl-Wostl, C. (2019). The role of governance modes and meta-governance in the transformation towards sustainable water governance. Environmental science & policy, 91, 6-16.

Penny, G., Müller-Itten, M., De Los Cobos, G., Mullen, C., & Müller, M. F. (2021). Trust and incentives for transboundary groundwater cooperation. Advances in Water Resources, 155, 104019.

Perret, S. R., & Stevens, J. B. (2006). Socio-economic reasons for the low adoption of water conservation technologies by smallholder farmers in southern Africa: a review of the literature. Development Southern Africa, 23(4), 461-476.

Peterson, G., Allen, C.R., Holling, C.S. (1998). Ecological Resilience, Biodiversity, and Scale 13.

Petit, J., Ait-Mouheb, N., García, S. M., Metz, M., Molle, B., & Bendoula, R. (2021). Potential of visible/near infrared spectroscopy coupled with chemometric methods for discriminating and estimating the thickness of clogging in drip-irrigation. Biosystems Engineering, 209, 246-255.

Pietrucha-Urbanik, K., & Rak, J. R. (2020). Consumers' perceptions of the supply of tap water in crisis-situations. Energies, 13(14), 3617.

Platt, S. (2000). Current Development of the Population in the Provinces of Ouarzazate and Zagora. Impetus Atlas Morocco: Research Results, 2007, 59-60.

Poteete, A. R., Janssen, M. A., & Ostrom, E. (2010). Working together: collective action, the commons, and multiple methods in practice. Princeton University Press.

Quintas-Soriano, C., Brandt, J., Baxter, C. V., Bennett, E. M., Requena-Mullor, J. M., & Castro, A. J. (2022). A framework for assessing coupling and de-coupling trajectories in river social-ecological systems. Sustainability Science, 1-14.

R Core Team. (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rademacher-Schulz, C. (2014). The making of the social order–migration, resource, and power conflicts in the Moroccan Draa Valley. Erdkunde, 173-183.

Ramasamy, R., Surendran, S. (2012). Global Climate Change and Its Potential Impact on Disease Transmission by Salinity-Tolerant Mosquito Vectors in Coastal Zones. Frontiers in Physiology 3.

Rapoport, A., & Au, W. T. (2001). Bonus and penalty in common pool resource dilemmas under uncertainty. Organizational behavior and human decision processes, 85(1), 135-165.

Raudsepp-Hearne, C., Peterson, G. D., & Bennett, E. M. (2010). Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proceedings of the National Academy of Sciences, 107(11), 5242-5247.

Reid, W. V., Mooney, H. A., Cropper, A., Capistrano, D., Carpenter, S. R., Chopra, K., ... & Zurek, M. B. (2005). Ecosystems and human well-being-Synthesis: A report of the Millennium Ecosystem Assessment. Island Press.

Revenga, C., Murray, S., Abramovitz, J., & Hammond, A. (1998). Watersheds of the world: ecological value and vulnerability. World Resources Institute, (pp. 172-pp).

Reyers, B., Biggs, R., Cumming, G. S., Elmqvist, T., Hejnowicz, A. P., & Polasky, S. (2013). Getting the measure of ecosystem services: a social-ecological approach. Frontiers in Ecology and the Environment, 11(5), 268-273.

Riesco, M., Delibes, M., Calzada, J., Esquivias, J., Qninba, A., Clavero, M. (2020). Desert otters: Distribution, habitat use and feeding ecology in arid rivers of Morocco. Journal of Arid Environments 178, 104165. https://doi.org/10.1016/j.jaridenv.2020.104165

Rist, S., Chidambaranathan, M., Escobar, C., Wiesmann, U., & Zimmermann, A. (2007). Moving from sustainable management to sustainable governance of natural resources: The role of social learning processes in rural India, Bolivia, and Mali. Journal of rural studies, 23(1), 23-37.

Robards, M. D., Schoon, M. L., Meek, C. L., & Engle, N. L. (2011). The importance of social drivers in the resilient provision of ecosystem services. Global Environmental Change, 21(2), 522-529.

Robinson, L. A., & Hammitt, J. K. (2011). Behavioral economics and regulatory analysis. Risk Analysis: An International Journal, 31(9), 1408-1422.

Rockström, J., Falkenmark, M., Allan, T., Folke, C., Gordon, L., Jägerskog, A., ... & Varis, O. (2014). The unfolding water drama in the Anthropocene: towards a resilience-based perspective on water for global sustainability. Ecohydrology, 7(5), 1249-1261.

Rodríguez, J. P., Beard Jr, T. D., Bennett, E. M., Cumming, G. S., & Cork, S. 3. et al. (2006). Trade-offs across space, time, and ecosystem services. Ecol. Soc, 11, 28.

Rodríguez-Ortega, T., Oteros-Rozas, E., Ripoll-Bosch, R., Tichit, M., Martín-López, B., & Bernuès, A. (2014). Applying the ecosystem services framework to pasture-based livestock farming systems in Europe. Animal, 8(8), 1361-1372.

Royaume du Maroc (2002). Moroccan standards for surface water quality (2002). Official Bulletin No 5062. http://www.sgg.gov.ma/BO/fr/2002/bo_5062_fr.pdf. Accessed 09.12.2021

Royaume du Maroc (2006). Norme Marocaine Homologuée : Qualité des Eaux d'Alimentation Humaine. NM 03.7.001

Royaume du Maroc (2008). Fiche sur le nouveau système d'évaluation de la qualité des eaux.

Royaume du Maroc - Agence du Bassin Hydraulique du Souss Massa Draa (ABHSMD) (2010). Etude D'evaluation Des Ressources En Eau Souterraines Dans Les Bassins De Draa Et Guelmim. Mission I : Synthèse Hydrogéologique des Unités Aquifères, Agadir, p. 120.

Royaume du Maroc (2019). 2020-2050 National Water Plan : Ministère de l'Equipement, transport, logistiques et de l'eau.

Royaume du Maroc - Agence du Bassin Hydraulique Draa Oued Noun (2020). Etude D'elaboration Du Contrat De Nappe De Faija. Mission I-II-III : Etat des lieux, tendance de l'évolution future et identification d'axes stratégiques d'amélioration de la situation actuelle.

Ruskule, A., Vinogradovs, I., & Pecina, M. V. (2018). The Guidebook on "The Introduction to the Ecosystem Service Framework and its Application in Integrated Planning". University of Latvia, Faculty of Geography and Earth Science: Riga, Latvia.

Russell, R., Guerry, A.D., Balvanera, P., Gould, R.K., Basurto, X., Chan, K.M., Klain, S., Levine, J., Tam, J. (2013). Humans and nature: how knowing and experiencing nature affect well-being. Annual review of environment and resources 38, 473–502.

Sagie, H., Morris, A., Rofè, Y., Orenstein, D. E., & Groner, E. (2013). Cross-cultural perceptions of ecosystem services: A social inquiry on both sides of the Israeli–Jordanian border of the Southern Arava Valley Desert. Journal of Arid Environments, 97, 38-48.

Saldaña, J. (2021). The coding manual for qualitative researchers.

Samraoui, B., Bouhala, Z., Chakri, K., Márquez-Rodríguez, J., Ferreras-Romero, M., El-Serehy, H.A., Samraoui, F., Sartori, M., Gattolliat, J.-L. (2021). Environmental determinants of mayfly assemblages in the Seybouse River, north-eastern Algeria (Insecta: Ephemeroptera). Biologia 76, 2277–2289.

Sandifer, P.A., Sutton-Grier, A.E., Ward, B.P. (2015). Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: Opportunities to enhance health and biodiversity conservation. Ecosystem Services 12, 1–15. https://doi.org/10.1016/j.ecoser.2014.12.007

Schneider, F., Fry, P., Ledermann, T., & Rist, S. (2009). Social learning processes in Swiss soil protection—the ‘from farmer-to farmer ‘project. Human ecology, 37, 475-489.

Schoengold, K., & Brozovic, N. (2018). The future of groundwater management in the high plains: evolving institutions, aquifers and regulations. In Western Economics Forum (Vol. 16, No. 1, pp. 47-53).

Schulz, O. (2007). Analyse schneehydrologischer Prozesse und Schneekartierung im Einzugsgebiet des Oued M’Goun, Zentraler Hoher Atlas (Marokko) (Doctoral dissertation, Universitäts-und Landesbibliothek Bonn).

Schütze, N., Thiel, A., Paneque, P., Vargas, J., & Vidaurre, R. (2020). Strengthening coordination in river basin governance in southern Spain: Cooperation, incentives and persuasion (No. 18/2020). Briefing Paper.

SEEE (2007). Normes de Qualité. Eaux destinées à l‘irrigation.

Sellam, N., A. Viñolas, F. Zouggaghe, & R. Moulaï. (2019). Assessment of the physico-chemical and biological quality of surface waters in arid and semi-arid regions of Algeria (North Africa). Bulletin de la Société zoologique de France 144(4): 157-178.

Shabman, L. A., & Batie, S. S. (1978). Economic value of natural coastal wetlands: a critique. Coastal Management, 4(3), 231-247.

Shalsi, S., Ordens, C. M., Curtis, A., & Simmons, C. T. (2022). Coming together: Insights from an Australian example of collective action to co-manage groundwater. Journal of Hydrology, 608, 127658.

Shan, Y., Yang, L., Perren, K., & Zhang, Y. (2015). Household water consumption: insight from a survey in Greece and Poland. Procedia Engineering, 119, 1409-1418.

Shiferaw, B., Freeman, H. A., & Swinton, S. M. (Eds.). (2005). Natural resources management in agriculture: Methods for assessing economic and environmental impacts. CABI.

Shogren, J. F., & Taylor, L. O. (2008). On behavioral-environmental economics. Review of Environmental Economics and Policy.

Silvano, R. A., Udvardy, S., Ceroni, M., & Farley, J. (2005). An ecological integrity assessment of a Brazilian Atlantic Forest watershed based on surveys of stream health and local farmers' perceptions: implications for management. Ecological Economics, 53(3), 369-385.

Silva-Novoa Sánchez, L.M., Bossenbroek, L., Schilling, J. and Berger, E. (2022) ‘Governance and Sustainability Challenges in the Water Policy of Morocco 1995–2020: Insights from the Middle Draa Valley’, Water, 14(18), p. 2932. https://doi.org/10.3390/w14182932.

Slough, T., Rubenson, D., Levy, R. E., Alpizar Rodriguez, F., Bernedo del Carpio, M., Buntaine, M. T., ... & Zhang, B. (2021). Adoption of community monitoring improves common pool resource management across contexts. Proceedings of the National Academy of Sciences, 118(29), e2015367118.

Smith, M. J., Wagner, C., Wallace, K. J., Pourabdollah, A., & Lewis, L. (2016). The contribution of nature to people: Applying concepts of values and properties to rate the management importance of natural elements. Journal of Environmental Management, 175, 76-86.

Souilmi, F., K. Ghedda, A. Fahde, F. E. Fihri, S. Tahraoui, F. Elasri, & M. Malki. (2019). Taxonomic diversity of benthic macroinvertebrates along the Oum Er Rbia River (Morocco): implications for water quality bio-monitoring using indicator species. West African Journal of Applied Ecology 27(1): 137–149.

Sousa, L. P., Lillebø, A. I., Gooch, G. D., Soares, J. A., & Alves, F. L. (2013). Incorporation of local knowledge in the identification of Ria de Aveiro lagoon ecosystem services (Portugal). Journal of Coastal Research, (65), 1051-1056.

SRTT (Sir Ratan Tata Trust & Navajbai Ratan Tata Trust) (2011) Salinity Prevention and Mitigation Initiative.

Šteflová, M., Koop, S. H. A., Fragkou, M. C., & Mees, H. (2022). Desalinated drinking-water provision in water-stressed regions: Challenges of consumer-perception and environmental impact lessons from Antofagasta, Chile. International Journal of Water Resources Development, 38(5), 742-765.

Stevenson, E.G., Greene, L.E., Maes, K.C., Ambelu, A., Tesfaye, Y.A., Rheingans, R., Hadley, C. (2012). Water insecurity in 3 dimensions: an anthropological perspective on water and women’s psychosocial distress in Ethiopia. Social science & medicine 75, 392–400.

Stubbington, R., Bogan, M.T., Bonada, N., Boulton, A.J., Datry, T., Leigh, C., Vander Vorste, R. (2017). Chapter 4.3 - The Biota of Intermittent Rivers and Ephemeral Streams: Aquatic Invertebrates, in: Datry, T., Bonada, N., Boulton, A. (Eds.), Intermittent Rivers and Ephemeral Streams. Academic Press, pp. 217–243. https://doi.org/10.1016/B978-0-12-803835-2.00007-3

Sullivan, C. A., Meigh, J. R., & Giacomello, A. M. (2003). The water poverty index: development and application at the community scale. In Natural resources forum (Vol. 27, No. 3, pp. 189-199). Oxford, UK: Blackwell Publishing Ltd.

Sundberg, S. (2004). Replacement costs as economic values of environmental change: A review and an application to Swedish sea trout habitats. Stockholm: Beijer International Institute of Ecological Economics.

Symes, D. (2006). Fisheries governance: A coming of age for fisheries social science? Fisheries research, 81(2-3), 113-117.

Tachet, H., P. Richoux, M. Bournaud, & P. Usseglio-Polatera. (2010). Invertébrés d’eau douce: systématique, biologie, écologie. CNRS édition Paris.

Tang, Z., Nan, Z., & Liu, J. (2013). The willingness to pay for irrigation water: A case study in Northwest China. Global Nest Journal, 15(1), 76-84.

Tengö, M., Hill, R., Malmer, P., Raymond, C. M., Spierenburg, M., Danielsen, F., ... & Folke, C. (2017). Weaving knowledge systems in IPBES, CBD, and beyond—lessons learned for sustainability. Current opinion in environmental sustainability, 26, 17-25.

Terink, W., Immerzeel, W.W., Droogers, P. (2013). Climate change projections of precipitation and reference evapotranspiration for the Middle East and Northern Africa until 2050. International Journal of Climatology 33, 3055–3072. https://doi.org/10.1002/joc.3650

Terrapon-Pfaff, J. C., Viebahn, P., Ersoy, S. R., & Schomberg, A. (2021). Concentrated solar power plant: Noor-I, Draa-Valley, Morocco.

Theesfeld, I. (2010). Institutional challenges for national groundwater governance: Policies and issues. Groundwater, 48(1), 131-142.

Touabay, M., N. Aouad, & J. Mathieu. (2002). Etude Hydrobiologique d'un cours d'eau du Moyen-Atlas : l'oued Tizguit (Maroc). Annales de Limnologie-International Journal of Limnology. EDP Sciences 38(1): 65–80. https://doi.org/10.1051/limn/2002007

Tramblay, Y., Jarlan, L., Hanich, L., Somot, S. (2018). Future Scenarios of Surface Water Resources Availability in North African Dams. Water Resources Management 32. https://doi.org/10.1007/s11269-017-1870-8

Travers, H., Clements, T., Keane, A., & Milner-Gulland, E. J. (2011). Incentives for cooperation: The effects of institutional controls on common pool resource extraction in Cambodia. Ecological Economics, 71, 151-161.

Tripler, E., Shani, U., Mualem, Y., Ben-Gal, A. (2011). Long-term growth, water consumption and yield of date palm as a function of salinity. Agricultural Water Management 99, 128–134.

Uddin, M. N., Bokelmann, W., & Entsminger, J. S. (2014). Factors affecting farmers' adaptation strategies to environmental degradation and climate change effects: A farm level study in Bangladesh. Climate, 2(4), 223-241.

Uh, H.-W., Hartgers, F.C., Yazdanbakhsh, M., Houwing-Duistermaat, J.J. (2008). Evaluation of regression methods when immunological measurements are constrained by detection limits. BMC Immunol 9, 59. https://doi.org/10.1186/1471-2172-9-59

van Vuren, G., Papin, C., & El Haouari, N. (2004). Participatory Irrigation Management: comparing theory with practice a case study of the Beni Amir irrigation scheme in Morocco. In Séminaire sur la modernisation de l'agriculture irriguée (pp. 11-p). IAV Hassan II.

Varady, R. G., Zuniga-Teran, A. A., Gerlak, A. K., & Megdal, S. B. (2016). Modes and approaches of groundwater governance: A survey of lessons learned from selected cases across the globe. Water, 8(10), 417.

Vatn, A. (2009). Cooperative behavior and institutions. The Journal of Socio-Economics, 38(1), 188-196.

Velasco, J., Millán, A., Hernández, J., Gutiérrez, C., Abellán, P., Sánchez, D., Ruiz, M. (2006). Response of biotic communities to salinity changes in a Mediterranean hypersaline stream. Aquat. Biosyst. 2, 12. https://doi.org/10.1186/1746-1448-2-12

Verbi Software. (2020). MAXQDA, Software für qualitative Datenanalyse.

Vignola, R., Koellner, T., Scholz, R. W., & McDaniels, T. L. (2010). Decision-making by farmers regarding ecosystem services: Factors affecting soil conservation efforts in Costa Rica. Land use policy, 27(4), 1132-1142.

Vira, B., Adams, B., Agarwal, C., Badiger, S., Hope, R. A., Krishnaswamy, J., & Kumar, C. (2012). Negotiating trade-offs: choices about ecosystem services for poverty alleviation. Economic and Political Weekly, 67-75.

Wallace, J.B., Webster, J.R. (1996). The role of macroinvertebrates in stream ecosystem function. Annual review of entomology 41, 115–139.

Wang, Z., Li, J., Lai, C., Zeng, Z., Zhong, R., Chen, X., ... & Wang, M. (2017). Does drought in China show a significant decreasing trend from 1961 to 2009? Science of the Total Environment, 579, 314-324.

Warner, N., Lgourna, Z., Bouchaou, L., Boutaleb, S., Tagma, T., Hsaissoune, M., Vengosh, A. (2013). Integration of geochemical and isotopic tracers for elucidating water sources and salinization of shallow aquifers in the sub-Saharan Drâa Basin, Morocco. Applied Geochemistry 34, 140–151.

Wickham, H., Francois, R., Henry, L., Müller, K. (2015). dplyr: A grammar of data manipulation. R package version 0.4 3, p156.

Wight, C., Garrick, D., & Iseman, T. (2021). Mapping incentives for sustainable water use: global potential, local pathways. Environmental Research Communications, 3(4), 041002.

Williams, W.D. (1999). Salinization: A major threat to water resources in the arid and semi-arid regions of the world. Lakes & Reservoirs: Research & Management 4, 85–91.

Woodhouse, P., & Muller, M. (2017). Water governance—A historical perspective on current debates. World Development, 92, 225-241.

World Commission on Dams. (2000). Dams and development: A new framework for decision-making: The report of the World Commission on dams. Earthscan.

Wright, J., Gundry, S., Conroy, R. (2004). Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. Tropical Medicine & International Health 9, 106–117. https://doi.org/10.1046/j.1365-3156.2003.01160.x

Wutich, A., Brewis, A., Chavez, J.B.R., Jaiswal, C.L. (2016). Water, worry, and Doña Paloma: why water security is fundamental to global mental health, in: Global Mental Health. Routledge, pp. 57–72.

Wutich, A., Ragsdale, K. (2008). Water insecurity and emotional distress: coping with supply, access, and seasonal variability of water in a Bolivian squatter settlement. Social science & medicine 67, 2116–2125.

Yasri, N. (2009). Diversité, écologie et biolgéographie des macroinvertebrés de quelques affluents du Mazafran. (Doctoral dissertation, Alger).

Yu, C., Huang, X., Chen, H., Huang, G., Ni, S., Wright, J. S., ... & Yu, L. (2018). Assessing the impacts of extreme agricultural droughts in China under climate and socioeconomic changes. Earth's Future, 6(5), 689-703.

Yu, Y., & de Dear, R. (2022). Thermal respite for pedestrians in overheated urban environments–Introduction of a dynamic analysis of outdoor thermal comfort. Sustainable Cities and Society, 86, 104149.

Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L., Tockner, K. (2015). A global boom in hydropower dam construction. Aquat Sci 77, 161–170. https://doi.org/10.1007/s00027-014-0377-0

Zerouali, S., Yacoubi-Khebiza, M., & El Qorchi, F. (2019). Monetary Value Change of Some Provisioning Ecosystem Services of Middle Draa Valley, South of Morocco. In Climate Change and Its Impact on Ecosystem Services and Biodiversity in Arid and Semi-Arid Zones (pp. 67-77). IGI Global.

Zhang, W., Kato, E., Bhandary, P., Nkonya, E., Ibrahim, H. I., Agbonlahor, M., ... & Cox, C. (2016). Awareness and perceptions of ecosystem services in relation to land use types: Evidence from rural communities in Nigeria. Ecosystem Services, 22, 150-160.

Zou, H., Hastie, T. (2005). Regularization and variable selection via the elastic net. Journal of the Royal Statistical Society: Series B (Statistical Methodology) 67, 301–320. https://doi.org/10.1111/j.1467-9868.2005.00503.x

Zuo, Q., Hao, M., Zhang, Z., Jiang, L. (2020). Assessment of the Happy River Index as an Integrated Index of River Health and Human Well-Being: A Case Study of the Yellow River, China. Water 12, 3064. https://doi.org/10.3390/w12113064

Zwarteveen, M., Kemerink-Seyoum, J. S., Kooy, M., Evers, J., Guerrero, T. A., Batubara, B., ... & Wesselink, A. (2017). Engaging with the politics of water governance. Wiley Interdisciplinary Reviews: Water, 4(6), e1245.

Zwarteveen, M., Kuper, M., Olmos-Herrera, C., Dajani, M., Kemerink-Seyoum, J., Frances, C., ... & De Bont, C. (2021). Transformations to groundwater sustainability: From individuals and pumps to communities and aquifers. Current Opinion in Environmental Sustainability, 49, 88-97.

Appendix

Table S 2. 1. Interview guides for stakeholder groups

Interview guide for local inhabitants	
1.	In your opinion, what is the role of water in the oasis? How important are the water releases from the dam for the oasis? What is the role of groundwater in the water use of the oasis?
2.	How many times do you need to receive river water per year? For which purpose do you use it?
3.	What are the benefits you get from water supplied to the oasis?
4.	We know that you need water to do farming and to secure your family's food, as well as for other domestic uses such as cooking and cleaning. But we would like you to tell us more about water. What does it mean for you?
5.	What do you feel when you receive your water share?
6.	If I ask you to put in order of priority the services you mentioned, what would the order look like?
7.	From your perspective, do you think there is good coordination between the provision of river water to the MDV by the respective authorities and the local distribution systems in the oases?
8.	What can you tell me about the new dam project taking place in the valley?
9.	We learned that the WUA plays the role of an intermediary between the people of the oases and the governmental institutions, what do you think about your oasis' WUA? How does it contribute to the benefits you perceive from water?
Interview guide for governmental actors	
1.	You as a regional institution or regional actor in the Draa Valley, from your point of view, what are the advantages or benefits that exist in the region even the water resources?
2.	Can you indicate the benefits that are present only in the Middle Valley of Drâa?
3.	From your point of view, which of the water-related benefits you mentioned are essential for local people or otherwise directly related to the livelihoods of local people in the valley?
4.	And if I ask you to put all the benefits you mentioned in order, what would that order look like?
5.	And can you explain to me based on which criteria you ordered the benefits you mentioned?
6.	Looking at the different development strategies and policies put in place to manage water, which sectors do you think are most promoted/supported? Why or why not?
7.	What products do you think are primarily promoted by the government?
8.	What do you think of the current dam policy?
9.	What local institutions are you in contact with?
10.	We have learned that there will be a new dam in the MDV. Could you tell us more about it? What are the objectives behind it?
11.	What criteria were considered in planning the dam? How will this dam contribute to the well-being of the local population? How were the local people consulted in the decision-making and implementation of the project?

Table S 2. 2. Code System derived from interview responses of local inhabitants using three categories of ecosystem services (MAXQDA 2020).

Parent code, Codes, and subcodes	Number of times the code was mentioned	Percentage (%)
Q1. Provisioning services	**203**	**54,86**
Q1.1 Domestic water use	35	9,45
Q1.2 Drinking water	42	11,35
Q1.3 crop production	74	19,99
• *Q1.3.1 Alfalfa, Cereals*	*26*	*7,02*
• *Q1.3.2 Dates*	*32*	*8,64*
• *Q1.3.3 Vegetables*	*16*	*4,32*
Q1.4 irrigation water	57	15,40
Q2. Cultural services	**153**	**41,35**
Q2.1 emotional comfort and satisfaction	32	8,64
Q2.2 Traditional knowledge	40	10,81
Q2.3 recreation	1	2,70
Q2.4 Scenic value	26	7,02
Q2.5 sense of place	54	14,59
Q3. Regulating services	**14**	**3,79**
Q3.1 climate regulation	14	3,79
Total	**370**	**100**

Table S 2. 3. Code System derived from interview responses of governmental actors using three categories of ecosystem services (MAXQDA 2020).

Parent code, Codes, and Subcodes	Number of Times the code was mentioned	Percentage (%)
Q1. Provisioning services	**87**	**94.56**
Q1.1 Drinking water	28	32.18
Q1.2 crop production	23	26.43
• *Q1.2.1 Alfalfa, wheat barley*	*8*	*9.19*
• *Q1.2.2 Dates*	*10*	*11.49*
• *Q1.2.3 Vegetables*	*5*	*5.74*
Q1.3 irrigation water	25	28.73
Q1.4 Energy production	5	5.74
Q1.5 Domestic usages	6	6.89
Q2. Cultural services	**5**	**5,43%**
Q2.1 recreation	3	3,26
Q2.3 sense of place	2	2.17
Total	**92**	**100**

Table S 2. 4. Expressions or quotes of ecosystem services identification by local inhabitants.

Ecosystem services	Quotes and expressions of local inhabitants
Provisioning services	
Drinking water	*"We also use water for drinking, 16 years now, we have water supplied to us through taps from water towers thanks to an association." (farmer)*
Domestic water	*"We use water in the canals for other uses also such as the washing activities of carpets, cloths and so on" (household member)*
Irrigation water	*"When the water arrives, the dam is filled and the water flows through the Saguias attached to it, we irrigate our lands". (housemaid)*
Crop production	*"I cultivate wheat and vegetables for summer, but my main focus is date production. I produce dates and I sell them in different markets here and in cities, I also buy from other farmers" (Farmer).*
	"I do agriculture only. I do wheat, Alfalfa, vegetables like eggplant and Gombos. For these I need to water almost every week. I also cultivate dates" (farmer)
Cultural services	
Sense of Place and Identity	*"People irrigate to produce first dates, one of the most important products in the area, which also makes their identity in the area" (student).*
	"The relationship with the nature in oasis and the lands is very strong. As farmers, our land is part of us, it's like a member of our family. We have to take from our resources and feed them as well to keep them alive and good enough to give. We are attached to our land, to the oasis, and our lifestyle here."
Traditional knowledge	*"The Nouba(turn) system we use to distribute water existed for almost 400 years now. We started learning about it when we were young, we started being a part of the distribution process and helping to work the canals at a very young age, which made it easy for us to understand and keep using the system clearly until now" (farmer).*
Emotional comfort and satisfaction	*"It feels good to receive my water share. I feel that I am ok and happy and satisfied that I was able to irrigate my lands and my palm trees" (Farmer).*
Scenic beauty	*"Water flow is good to experience the oases green and beautiful, for us and the people visiting sometimes" (Resident).*
	"When we receive water, we have more green spaces and we feel good about that" (Farmer) *"water is good for the beauty of the area" (Farmer)*
Recreation	*"the economy of the area is based on agriculture first, but also recreation and tourism too" (Cooperative member)*
Regulating services	
Climate regulation	*"Water we receive from the dam is also important for climate regulation, the water released helps smooth the aridity of the weather a little bit which is of a direct positive impact on us" (Household member).*

Appendix 3. 1. Cost-based survey questionnaire.

I. Semi-structured interview:

1. Since when do you live here?
2. Are you practicing agriculture?
3. In what way do you rely on the natural resource of water? Which benefits do you get from water in this area?
4. Have you felt a change in the availability of water within the last 20 years?
5. How did the availability change in that period?
6. What consequences did those changes have for your household?
7. What did you do specifically to adapt to these changes, e.g. did you try to increase the availability of water or did you change your agricultural practices? What pushed you to do so?
8. To what extent have you been able to compensate for any losses or decreased production possibilities due to a lower availability of water?

II. Questionnaire

9. **How much agricultural surface are you using?**
   a. ☐ Less than 5 hectares
   b. ☐ Between 5 and 10 hectares
   c. ☐ More than 10 hectares
10. **Water sources are you using for irrigation? And for drinking?**
    a. ☐River water ☐ River water
    b. ☐Groundwater ☐ Groundwater
11. **Can you estimate your annual income from agriculture in 2021?** ……………….
    a. Products and quantities: ……………………………………………………………………………

12. **How many wells do you have? 1 2 3 4 5 6 7 8 9 10 11 12 13 ….**

13. **Please take a look at this schematic picture/map of the area where you live and produce. (Show Drâa river, ask for the location of the road, distances between the road and Drâa, location of the village, current location, location of plots and wells, etc.)**

14. **How many of these:**
    a. Were dug within the existing saguia system?............
       i. ☐ Do you use them as the main water supply for your plots? (full replacement)
       ii. ☐ Do you use them primarily when there is no water in the river? (partial replacement)
    b. Were dug as an extension, e.g. outside of the area of the existing saguia system? (Extension)..................
15. **What was the reason for building these wells (if possible please specify for each well)?**
    a. Attributions: ☐ getting better water quality ☐ increasing water supply

       ☐ Irrigation ☐ Drinking
16. **After constructing the wells, did you fully recover the previous water supply in quantity and quality? Do you have the same amount of water as before? Or more? Or less?**
    a. ☐ 100%
    b. ☐ > 100% (more)
    c. ☐ < 100% (less)

Appendix 3.1. (Continued)

1. What did you do to replace/improve the water <u>quantity</u> <u>of the river</u>?

Digging wells / Costs	Water source prospection	Hiring Workers	Raw material			Water pump		Building around the well	Year
			Cement	Metals	Rocks…	Engine	Pump		
Buying water litres									
Renting pumping hours									
Water transfer from wells to lands (cisterna, plastic tubes)									
Monthly payment for the collective wells' use (for drinking)									

2. What did you do to replace/improve the water <u>quality of the river</u>?

3. What do you do to have access to more water if your wells get dry?

Digging New wells / Costs	Water source prospection	Hiring Workers	Raw Material			Water pump		Building around the well	Year
			Cement	Metals	Rocks…	Engine	Pump		
Deepening the well / Costs	**Hiring Workers**	**Raw material**			**…**	**…**	**…**	**…**	**Year**
Buying or transporting water from other wells									

4.What do you do to have access to groundwater with good quality?

Deepening the well to the confined aquifer						
Pump the water to a surface water basin						
Buy water litters pumped from other wells						

Appendix 3.1. (Continued).

17. **Do you produce dates?**
    ☐ Yes ☐ No
18. **Was your date production affected by a decrease in water supply in the past 30 year**☐ Yes☐ No
19. **If yes, can you specify when? ………………….**
20. **Did you adapt your date production due to this?** ☐Yes ☐ No
21. **If yes, how did you adapt your date fruit production?**
    a. ☐ By reducing the quantities produced
    b. ☐ By changing the varieties produced
    c. ☐ By reducing the irrigated palm trees
    d. …………………………………………………………
    e. …………………………………………………………
    f. …………………………………………………………
22. **Do you still produce the same varieties?**
    ☐ Yes ☐ No

Before/After the water supply shortages	**Varieties produced**	**Quantities**	**Price/KG**	**Year**

23. **How did your income from dates change?**
    a. Income before water shortage occurred…………………………………………….
    b. Income after water shortage occurred………………………………………….
24. **How did the date quantities you produce change?**
    a. Quantities before water shortage occurred……………………………………………….
    b. Quantities after water shortage occurred
    ………
25. **How did you adapt your basic crop production? (e.g. vegetables, wheat, barley…)**
    a. Do you still produce them on your own? ☐Yes ☐ No
        i. ☐Fully
        ii. ☐Partially
        iii. Which ones?..
    b. Do you buy them from the local market? ☐Yes ☐ No
        i. ☐Fully
        ii. ☐Partially
        iii. How much you spend per week?..
    c. You borrow them from neighbors?
        i. ☐Fully
        ii. ☐Partially
        iii. Which ones?..

Appendix 3.1. (Continued).

26. **Do you work in cities?** ☐ **Yes** ☐ **No**
    a. ☐ Full-time ☐ Part-time
    b. For which reason?...
    c. How much income do you gain? …………………………………………………………………………………………..
    d. In which way do you use this income?...
27. **Do you have a family member who migrated to work abroad?** ☐ **Yes** ☐ **No**
    a. If yes, for what reason?...
    b. Do you receive any remittances from them**?** ☐ **Yes** ☐ **No**
    c. If yes, how much remittances do you perceive?...

In which way do you mostly use the remittances money?...

Table S 4. 1. Location, river characteristics, and physico-chemical parameters (for October 2021, March 2022, and the used mean values), ecosystem health metrics, and the indices: water quality index (WQI), biological quality index (BQI), and human satisfaction index (HIS), all with their range, mean and SD for all study sites, sorted by Upper, Middle, and Lower Draa (bold names). Red values were excluded from the analysis or set to a maximum level (in case of chloride >6000), as they represent measurement failures due to dilution or calibration problems. MAVD is the Maximum Admissible Value by Moroccan water quality standards for drinking water (Royaume du Maroc 2006), MAVI the Maximum Admissible Value (SEEE, 2007) for irrigation water.

N°	Name	Lat	Long	Alt	Width [m] '21	Width [m] '22	Width [m] Mean	Depth [cm] '21	Depth [cm] '22	Depth [cm] Mean	Flow velocity [m/s] '21	Flow velocity [m/s] '22	Flow velocity [m/s] Mean
	Upper Draa												
1	Ounila US	31.2617547	-7.1542015	1747	7.9	3.85	5.9	0.1	0.18	0.14	0.3	0.33	0.315
2	Ounila MS	31.146719	-7.140803	1412	8	6.7	7.4	0.2	0.16	0.18	0.44	0.3	0.37
3	El Mellah US	31.09406	-7.148652	1318	4	5	4.5	0	0.04	0.02	0.14	0.17	0.155
4	Iriri DS	30.945731	-7.199225	1252	8	8.2	8.1	0.3	0.15	0.225	0.07	0.07	0.07
5	Ait Douchen US	30.656967	-7.094667	1336	4	5.8	4.9	0.1	0.2	0.15	0	0.02	0.01
6	Ait Douchen DS	30.8652278	-6.84642778	1114	5	5	5.0	0.6	0.1	0.35	0.01	0.08	0.045
7	Dades High US	31.618608	-5.855497	1818	5.4	8.4	6.9	0.1	0.15	0.125	0.15	0.55	0.35
8	Dades (Gorges)	31.556222	-5.908688	1753	6	9.7	7.9	0.3	0.4	0.35	0.09	0.15	0.12
9	Dades MS	31.50473	-5.94536	1657	2	4.9	3.5	0.1	0.17	0.135	0.34	0.64	0.49
10	M'Goun US	31.365555	-6.171667	1547	16.6	11.5	14.1	0.3	0.3	0.3	0.47	0.55	0.51
11	M'Goun DS	31.330998	-6.182975	1511	5	12	8.5	0.2	0.23	0.215	0.18	0.56	0.37
12	Dades DS	31.01195	-6.49404	1188	13	8	10.5	0.2	0.5	0.35	0.02	0.52	0.27
	Middle Draa												
13	Tamnougalt	30.674778	-6.407056	904	-	-	-	-	-	-	0	0	0
	Lower Draa												
14	Akka Nait Sidi 1	29.911138	-7.33102	564	4	6	5.0	0.2	0.23	0.215	0.12	0.13	0.125
15	Akka Nait Sidi 2	29.9098167	-7.33021944	588	4	5.3	4.7	0.1	0.15	0.125	0.17	0.14	0.155
16	Tissint	29.822129	-7.196371	491	6	9.5	7.8	0.2	0.14	0.17	0.17	0.12	0.145
17	Mrimima	29.779739	-7.168112	461	11	6.5	8.8	0.2	0.16	0.18	0.08	0.16	0.12
Min				461	2.0	3.9	3.5	0.0	0.0	0.0	0.0	0.0	0.0
Max				1818	16.6	12.0	14.1	0.6	0.5	0.5	0.5	0.6	0.5
Mean				1198	6.9	7.3	7.1	0.2	0.2	0.2	0.2	0.3	0.2
SD				423	3.7	2.4	2.6	0.1	0.1	0.2	0.1	0.2	0.2
MAVD													
MAVI													

Table S 4.1. (Continued)

N°	Flow rate [m³/s] '21	Flow rate [m³/s] '22	Flow rate [m³/s] Mean	Temp [°C] '21	Temp [°C] '22	Temp [°C] Mean	pH '21	pH '22	pH Mean	Cond [µS/cm] '21	Cond [µS/cm] '22	Cond [µS/cm] Mean	Oxygen [mg/l] '21	Oxygen [mg/l] '22	Oxygen [mg/l] Mean
1	0.07	0.05	0.06	21.6	18.5	20.1	7.1	8.3	7.7	2810	2150	2480	7.99	2.7	8.0
2	0.14	0.06	0.1	20.7	18.3	19.5	7.9	8.3	8.1	3820	3080	3450	8.1	**2.9**	8.1
3	0	0.01	0.005	23.7	22.3	23.0	8.4	8.1	8.3	15370	19330	17350	11.59	**3.3**	11.6
4	0.03	0.02	0.025	19.8	16.1	18.0	7.8	8.5	8.1	649	613	631	8.44	3.3	8.4
5	0	0.01	0.005	22.4	20.1	21.3	7.7	7.8	7.8	1134	1137	1136	5.6	5.95	5.6
6	0.01	0.01	0.01	25.5	20.7	23.1	7.5	8.4	8.0	1239	1175	1207	14.02	3.3	14.0
7	0.02	0.15	0.085	12.5	8.7	10.6	8.2	8.5	8.4	626	677	652	12.45	3.4	12.5
8	0.04	0.13	0.085	17.5	14.2	15.9	8.5	8.4	8.5	1163	792	978	10.6	4.3	10.6
9	0.02	0.09	0.055	16.5	13.1	14.8	8.5	8.5	8.5	1077	779	928	9.09	3.5	9.1
10	0.45	0.54	0.495	19.5	15.1	17.3	8.4	8.4	8.4	1030	883	957	8.76	2.7	8.8
11	0.4	0.35	0.375	19.9	15.2	17.6	8.2	8.5	8.3	1087	861	974	8.7	3.1	8.7
12	0.01	0.49	0.25	21.3	13.2	17.3	8.0	8.4	8.2	1792	1182	1487	15.83	2.6	15.8
13	0	0	0	25.2	23	24.1	8.1	9.5	8.8	2500	260	1380	17.23	3.7	17.2
14	0.02	0.05	0.035	23.6	23.9	23.8	7.7	7.9	7.8	10220	10210	10215	9.6	10.12	9.6
15	0.02	0.02	0.02	25.6	20.9	23.3	7.3	7.8	7.5	5680	5620	5650	12.4	14.84	12.4
16	0.04	0.04	0.04	24.3	15.1	19.7	8.2	8.5	8.4	11210	11970	11590	11.16	NA	11.2
17	0.04	0.03	0.035	18.8	21.7	20.3	8.9	8.6	8.8	14240	13680	13960	8.72	NA	8.7
Min	0	0	0	12.5	8.7	10.6	7.1	7.8	7.5	626	260	631	5.6	-	5.6
Max	0.5	0.54	0.495	25.6	23.9	24.1	8.9	9.5	8.8	15370	19330	17350	17.2	-	17.2
Mean	0.08	0.12	0.10	21.1	17.7	19.4	8.0	8.4	8.2	4450	4376	4413	10.6	-	10.6
SD	0.13	0.17	0.14	3.4	4.1	3.5	0.5	0.4	0.3	4882	5616	5229	2.9	-	2.9
MAVD						-			6.5 - 8.5			2700			<5
MAVI						35			6.5 - 8.4			12000			-

Table S 4.1. (Continued)

N°	Cl^- [mg/l] '21	Cl^- [mg/l] '21	Cl^- [mg/l] '22	Cl^- [mg/l] Mean	SO_4^{2-} [mg/l] '21	SO_4^{2-} [mg/l] '22	SO_4^{2-} [mg/l] Mean	NO_3^- [mg/l] '21	NO_3^- [mg/l] '22	NO_3^- [mg/l] Mean	NO_2^- [mg/l] '21	NO_2^- [mg/l] '22	NO_2^- [mg/l] Mean
		Ion Chromatography											
1	1300		2000	1650	177	183	180	4.8	<4	3.4	<0.02	NA	0.01
2	5100		1600	3350	190	530	360	<4	<4	2	<0.02	NA	0.01
3	540000000	1756	73000	>6000	177	186	181.5	<4	<4	2	<0.02	NA	0.01
4	2400		200	1300	30	30	30	<4	<4	2	<0.02	NA	0.01
5	2100		300	1200	128	136	132	8	13.3	10.65	0.02	NA	0.02
6	2500		600	1550	148	139	143.5	<4	<4	2	<0.02	NA	0.01
7	2200		200	1200	117	102	109.5	5.1	6.6	5.85	0.02	NA	0.02
8	2800		300	1550	145	118	131.5	6.7	<4	4.35	<0.02	NA	0.01
9	2100		200	1150	143	118	130.5	<4	5.8	3.9	<0.02	NA	0.01
10	2400		200	1300	140	141	140.5	<4	5.5	3.75	<0.02	NA	0.01
11	2800		200	1500	173	144	158.5	<4	5.2	3.6	<0.02	NA	0.01
12	3200	113	100	1650	187	123	155	<4	5.8	4.8	0.07	NA	0.07
13	1500		200	850	4000	<20	10	<4	<4	2	0.02	NA	0.02
14	5600		3900	4750	172	180	176	9.7	13.9	11.8	0.05	NA	0.05
15	7300		3000	5150	216	166	191	12.8	11.2	12	0.05	NA	0.05
16	230000	1434	1500	>6000	168	154	161	<4	<4	2	<0.02	NA	0.01
17	105100000	1377	3000	>6000	8900	143	143	<4	<4	2	<0.02	NA	0.01
Min	1300	113	100	850	30.0	<20	10	<4	<4	2	<0.02	-	0.01
Max	540000000	1756	73000	>6000	8900	530	360	12.8	13.9	11.8	0.1	-	0.07
Mean	37963135	1170	5324	-	895	-	149	-	-	-	-	-	-
SD	127912118	627	16960	-	2196	-	71	-	-	-	-	-	-
MAVD				750			400			50			0.5
MAVI				350			250			-			-

Table S 4.1. (Continued)

N°	NH_4^+ [mg/l] '21	NH_4^+ [mg/l] '22	NH_4^+ [mg/l] Mean	$PO_4$3- [mg/l] '21	PO_4 [mg/l] '22	PO_4 [mg/l] Mean	K^+ [mg/l] '21	K^+ [mg/l] '22	K^+ [mg/l] Mean	TH [°d] '21	TH [°d] '22	TH [°d] Mean	CH [°d] '21	CH [°d] '22	CH [°d] Mean
1	<0.1	<0.1	0.05	1.1	<0.6	0.7	5	3	4	400	100	250	200	100	150
2	<0.1	<0.1	0.05	<0.6	<0.6	0.3	7	5	6	500	100	300	200	100	150
3	<0.1	<0.1	0.05	1.5	<0.6	0.9	28	40	34	800	600	700	200	100	150
4	<0.1	<0.1	0.05	1.1	<0.6	0.7	4	4	4	-	100	100	8	100	54
5	0.1	0.2	0.15	1.1	0.9	1.0	8	7	7.5	500	200	350	300	100	200
6	<0.1	<0.1	0.05	<0.6	<0.6	0.3	10	7	8.5	500	100	300	200	100	150
7	<0.1	<0.1	0.05	<0.6	<0.6	0.3	3	3	3	500	100	300	200	100	150
8	<0.1	<0.1	0.05	<0.6	<0.6	0.3	4	2	3	500	100	300	200	100	150
9	<0.1	<0.1	0.05	<0.6	<0.6	0.3	3	3	3	400	100	250	200	100	150
10	<0.1	<0.1	0.05	<0.6	<0.6	0.3	<2	<2	1	600	300	450	200	100	150
11	<0.1	<0.1	0.05	<0.6	<0.6	0.3	<2	<2	1	500	200	350	200	100	150
12	<0.1	<0.1	0.05	4.6	<0.6	2.5	6	3	4.5	600	200	400	200	100	150
13	<0.1	<0.1	0.05	1	<0.6	0.8	11	3	7	600	100	350	200	100	150
14	<0.1	<0.1	0.05	3.5	2.1	2.8	28	21	24.5	600	200	400	300	100	200
15	<0.1	<0.1	0.05	5.4	2.5	4.0	23	40	31.5	700	300	500	300	100	200
16	0.2	<0.1	0.125	0.9	<0.6	0.6	50	40	45	600	400	500	200	100	150
17	0.3	0.1	0.3	1.9	1.8	1.9	70	50	60	800	400	600	200	100	150
Min	<0.1	<0.1	0.05	<0.6	<0.6	<0.6	<2	<2	1	400	100	100	8	100	54
Max	0.3	0.2	0.3	5.4	2.5	4.0	70	50	60	800	600	700	300	100	200
Mean	-	-	-	-	-	-	-	-	-	569	212	376	206	100	153
SD	-	-	-	-	-	-	-	-	-	116	141	138	62	0	31
MAVD			0.5			-			-			-			-
MAVI			-			-			-			-			-

Table S 4.1. (Continued)

N°	Taxa richness	%EPT	IBMWP	IBGN	WQI	BQI	HSI
1	16	0.31	41	9	71	45	60
2	17	0.29	53	9	62	52	60
3	15	0.33	55	10	63	56	47
4	18	0.33	57	10	80	61	60
5	12	0.33	45	9	68	43	55
6	19	0.37	63	11	74	71	59
7	11	0.45	41	8	79	42	63
8	18	0.56	55	9	76	69	63
9	15	0.53	54	9	76	63	63
10	13	0.62	57	12	75	77	54
11	14	0.5	68	13	75	81	54
12	22	0.45	70	11	74	83	53
13	5	0.4	19	9	74	23	29
14	12	0.25	44	7	61	31	71
15	13	0.23	48	7	63	33	71
16	9	0.33	30	6	63	20	23
17	12	0.17	40	6	57	21	23
Min	5	0.17	19	6	78	20.0	23.0
Max	22	0.62	70	13	57	83.0	71.0
Mean	14.2	0.38	49	9.1	69	51.3	52.7
SD	3.9	0.12	13	1.9	6.7	20.5	14.4
MAVD							
MAVI							

Table S 4. 2. Questions and possible answer options used in the questionnaire.

Questions	Answer options
Water and crop quality	
1. What sources of water do you use for drinking?	- River water
	- Groundwater of the commune
	- ONEE tap water
	- ONEE truck delivered water
2. What source of water do you use for irrigation?	- River water
	- Groundwater
	- Other sources
3. How do you qualify the quality of the water you drink?	- Very bad
	- Bad
	- Neither good nor bad
	- Good
	- Very good
	- Excellent
4. How do you qualify the quality of the water you use for irrigation?	- Very bad
	- Bad
	- Neither good nor bad
	- Good
	- Very good
	- Excellent
5. How do you qualify the quality of the crops you produce?	- Very bad
	- Bad
	- Neither good nor bad
	- Good
	- Very good
	- Excellent
Health status	
6. On a scale of 1 (very bad) to 10 (excellent), how do you qualify your general health status?	- 1 – 10
7. Do you think the quality of water used in this village has some effects on the health of people?	- Yes
	- No
8. If yes, is this effect:	- Predominantly positive
	- Predominantly negative
9. Do you perceive the water to be salty?	- Yes, often
	- Yes, sometimes
	- No
10. How often do you experience physical diseases from the water salinity?	- Often
	- Sometimes
	- Never
11. How often do you experience emotional distress due to water salinity and/or scarcity?	- Often
	- Sometimes
	- Never
Satisfaction	
12. How satisfied are you with the following aspects in your area? Please use the categories (very unsatisfied, predominantly unsatisfied, predominantly satisfied, very satisfied) for your answer:	- The health care
	- The quantity of water resources
	- The quality of water resources
	- Your agricultural production possibilities
	- The conditions of the natural environment
13. Considering all these elements, how satisfied are you overall currently with your life?	- Very unsatisfied
	- Predominantly unsatisfied
	- Predominantly satisfied
	- Very satisfied
Demographic questions	
14. Gender	- Male
	- Female
15. Occupation	- Farming
	- Other services
16. Age category	- 10 to 20 years old
	- 20 to 40 years old
	- 40 to 70 years old
	- Over 70 years old

Table S 4. 3. Results of comparisons of response values for demographic groups.

Comparisons of demographic groups	Mean/SD Group 1	Mean/SD Group 2	Mean/SD Group 3	Mean/SD Group 4	F	df	p-value	Eta²
Gender	**Male**	**Female**	**-**	**-**				
Drinking water	3.94/0.94	3.89/0.79			0.1	1	0.75	
Irrigation water	3.78/0.96	3.64/1.13			0.76	1	0.38	
Crop quality	3.62/0.8	3.56/0.74			0.29	1	0.59	
Health status	7.42/1.53	7.02/1.18			3.25	1	0.07	
Satisfaction	1.44/0.58	1.35/0.6			0.91	1	0.34	
Occupation	**Farming**	**Other services**	**-**	**-**				
Drinking water ~ Occupation	3.97/0.85	3.88/0.94			0.45	1	0.5	
Irrigation water ~ Occupation	3.86/0.91	3.59/1.11			3.11	1	0.08	
Crop quality ~ Occupation	3.61/0.79	3.57/0.79			0.13	1	0.71	
Health status ~ Occupation	7.26/1.47	7.38/1.45			0.27	1	0.61	
Satisfaction ~ Occupation	1.38/0.55	1.42/0.64			0.97	1	0.33	
Age	**10-20 years**	**20-40 years**	**40-70 years**	**over 70 years**				
Drinking water ~ Age	3/1.22	3.94/0.89	3.87/0.77	4.23/1.07	2.83	3	0.04*	0.01
Irrigation water ~ Age	3/1	3.8/0.98	3.9/0.87	3.18/1.33	2.69	3	0.08	
Crop quality ~ Age	3.2/0.84	3.69/0.66	3.57/0.84	3.45/1.01	1.14	3	0.33	
Health status ~ Age	8.4/1.67 (ab)	7.72/1.19 (a)	7/1.45 (b)	6.4/1.64 (b)	7.46	3	0.0001*	0.12
Satisfaction ~ Age	1.2/0.45 (ab)	1.5/0.57 (a)	1.47/0.52 (a)	0.95/0.69 (b)	7.22	3	0.0001*	0.05

Table S 4. 4. Responses to questionnaires sorted by survey sites and subbasins (SB) showing gender (G; M = male, F = female), occupation (O; 1 = Farming, 0 = Other services), age category (A; 1 = 10-20 years old, 2 = 20-40, 3 = 40-70, 4 = over 70), source of drinking (SDr) and irrigation water (SIr; R = river water, G = groundwater, Tr = truck delivered water, Ta = tap water, O = other sources), quality of drinking water (Wdr), irrigation water (WIr) and crops (Crop; 1 = very bad, 2 = bad, 3 = neither good nor bad, 4 = good, 5 = very good, 6 = excellent), health status (Health) on a scale from 1 (very bad) to 10 (excellent), perceived saltiness of water (Salty; 0 = no, 1 = yes sometimes, 2 = yes often), physical and emotional distress by salinity and scarcity (0 = never, 1 = sometimes, 2 = often), and satisfaction with health care, quantity and quality of water resources, agricultural production possibilities, conditions of the natural environment and life overall (0 = very unsatisfied, 1 = predominantly unsatisfied, 2 = predominantly satisfied, 3 = very satisfied).

Site	SB	G	O	A	SDr	SIr	WDr	WIr	Crop	Health	Salty	Physical	Emotional	SatHealth	SatQuantity	SatQuality	SatAgriculture	SatEnvironment	SatLife
OunilaUS	UD	M	1	3	TrO	R	5	4	5	6	0	0	0	1	2	2	2	2	0
OunilaUS	UD	M	1	2	TrO	R	5	4	5	8	0	0	0	1	2	2	2	2	1
OunilaUS	UD	M	1	3	TrO	R	5	4	5	6	0	0	0	1	2	2	2	2	1
OunilaUS	UD	M	1	2	TrO	R	5	4	5	9	0	0	0	1	2	2	2	2	2
OunilaUS	UD	M	1	2	TrO	R	5	4	4	8	0	0	0	1	2	2	2	2	2
OunilaUS	UD	M	1	2	TrO	R	5	4	4	7	0	0	0	1	2	2	2	2	2
OunilaUS	UD	M	1	2	TrO	R	4	4	4	9	0	0	0	1	2	2	2	2	2
OunilaUS	UD	F	0	2	TrO	R	4	4	4	5	0	0	0	1	2	2	2	2	2
OunilaUS	UD	M	0	3	TrO	R	5	5	4	6	0	0	0	1	2	2	2	2	2
OunilaUS	UD	M	0	2	TrO	R	4	4	4	6	0	0	0	1	2	2	2	2	2
OunilaUS	UD	M	1	2	TrO	R	5	4	4	8	0	0	0	1	2	2	2	2	2
OunilaUS	UD	M	1	3	TrO	R	4	5	5	8	0	0	0	1	2	2	2	2	2
OunilaUS	UD	F	0	2	TrO	R	4	4	4	7	0	0	0	1	2	2	2	2	2
OunilaUS	UD	M	0	2	TrO	R	5	5	4	7	0	0	0	1	2	2	2	2	2
OunilaUS	UD	M	1	2	TrO	R	5	4	4	8	0	0	0	1	2	2	2	2	2
Ounila	UD	F	1	3	Tr	R	4	4	3	7	0	0	1	1	2	2	1	2	2
Ounila	UD	M	1	3	Tr	R	3	4	4	5	0	0	1	1	1	2	2	2	2
Ounila	UD	M	1	4	Tr	R	4	4	3	4	0	0	2	1	1	1	2	2	2
Ounila	UD	M	1	3	Tr	R	4	4	4	5	0	0	1	1	1	1	2	2	2
Ounila	UD	M	1	3	Tr	R	3	4	3	NA	0	0	1	1	1	1	2	2	2
Ounila	UD	M	1	2	Tr	R	3	4	4	7	0	0	1	1	2	2	1	2	2
Ounila	UD	M	1	3	Tr	R	3	4	4	7	0	0	1	1	1	1	1	2	2
Ounila	UD	F	1	3	Tr	R	4	4	3	6	0	1	2	1	2	2	1	2	2
Ounila	UD	F	1	3	Tr	R	4	4	4	9	1	0	1	1	1	1	1	2	2
Ounila	UD	F	1	2	Tr	R	4	4	4	9	1	0	1	1	1	1	1	2	2
Ounila	UD	M	1	3	Tr	R	3	4	4	8	1	0	1	1	1	1	2	2	2
Iriri	UD	M	1	2	G	RO	5	5	4	10	0	0	0	1	2	2	2	2	1
Iriri	UD	F	1	3	G	RO	5	5	4	6	0	0	0	1	2	2	2	2	2
Iriri	UD	F	0	4	G	RO	5	5	4	5	0	0	NA	1	2	2	2	2	1
Iriri	UD	M	1	2	G	RO	5	5	4	7	0	0	NA	1	2	2	2	2	2
Iriri	UD	M	1	2	G	RO	5	5	4	8	0	0	0	1	2	2	2	2	2
Iriri	UD	F	NA	3	G	RO	5	5	4	7	0	0	0	1	2	2	2	2	2
Iriri	UD	M	1	2	G	RO	5	5	4	8	0	0	0	1	2	2	2	2	2
Iriri	UD	M	1	2	G	RO	5	5	4	9	0	0	0	1	2	2	2	2	2
Iriri	UD	M	0	3	G	RO	5	5	4	10	0	0	0	1	2	2	2	2	2
Iriri	UD	M	1	2	G	RO	5	5	4	9	0	0	0	1	2	2	2	2	2

Table S 4.4. (continued)

Site	SB	G	O	A	SDr	SIr	WDr	WIr	Crop	Health	Salty	Physical	Emotional	SatHealth	SatQuantity	SatQuality	SatAgriculture	SatEnvironment	SatLife
Iriri	UD	F	1	2	G	RO	5	5	4	9	0	0	0	1	2	2	2	2	2
Iriri	UD	M	0	2	G	RO	5	5	4	7	0	0	0	1	2	2	2	2	2
AitDouchen	UD	M	0	3	G	O	4	4	4	9	0	0	0	0	2	2	2	2	1
AitDouchen	UD	M	1	2	G	O	4	4	4	8	0	0	0	0	2	2	2	2	1
AitDouchen	UD	M	0	2	G	O	4	4	4	7	0	0	0	0	2	2	2	2	1
AitDouchen	UD	M	1	2	G	O	4	4	4	9	0	0	0	1	2	2	2	2	1
AitDouchen	UD	F	0	3	G	O	4	4	4	6	0	0	0	1	2	2	2	2	2
AitDouchen	UD	M	0	3	G	O	4	4	4	5	0	0	0	0	2	2	2	2	1
AitDouchen	UD	M	0	2	G	O	4	4	4	6	0	0	0	0	2	2	2	2	2
AitDouchen	UD	M	0	3	G	O	4	4	4	NA	0	0	0	0	2	2	2	2	2
AitDouchen	UD	F	0	3	G	O	4	4	4	5	0	0	0	1	2	2	2	2	2
AitDouchen	UD	M	0	1	G	O	4	4	4	8	0	0	0	0	2	2	2	2	1
AitDouchen	UD	M	1	2	G	O	4	4	4	8	0	0	0	0	2	2	2	2	2
Tarmigte	UD	M	1	2	Ta	G	4	4	4	9	0	0	0	1	2	2	2	2	2
Tarmigte	UD	M	1	2	Ta	G	4	4	4	8	0	0	1	0	2	2	2	2	2
Tarmigte	UD	M	0	3	Ta	G	4	4	4	7	0	0	1	1	2	2	2	2	1
Tarmigte	UD	M	0	2	Ta	G	4	4	4	7	0	0	0	1	2	2	2	2	1
Tarmigte	UD	M	0	2	Ta	G	4	4	4	9	0	0	0	1	2	2	2	2	2
Tarmigte	UD	M	1	2	Ta	G	4	4	4	7	0	0	1	1	2	2	2	2	2
Tarmigte	UD	M	1	3	Ta	G	4	4	4	6	0	0	1	1	2	2	2	2	2
Tarmigte	UD	M	0	2	Ta	G	4	4	4	8	0	0	0	1	2	2	2	2	2
Tarmigte	UD	M	1	2	Ta	G	4	4	4	9	0	0	1	1	2	2	2	2	2
Tarmigte	UD	M	0	3	Ta	G	4	4	4	6	0	0	0	1	2	2	2	2	2
Dades	UD	M	1	3	G	R	3	4	4	5	0	0	1	1	2	1	1	2	2
Dades	UD	M	1	3	G	R	3	4	4	8	0	0	1	1	2	2	1	2	2
Dades	UD	F	1	2	G	R	3	4	4	8	0	0	1	1	2	2	1	2	2
Dades	UD	M	1	3	G	R	3	4	4	7	0	1	1	1	2	2	1	2	2
Dades	UD	M	0	2	G	R	3	4	4	7	0	1	1	3	2	2	1	2	2
Dades	UD	M	1	2	G	R	4	4	4	9	0	0	1	1	2	2	1	2	2
Dades	UD	M	1	3	G	R	4	4	4	6	0	0	1	1	2	2	1	2	2
Dades	UD	F	0	2	G	R	4	4	4	6	0	0	0	1	2	2	1	2	2
Dades	UD	M	1	2	G	R	4	4	4	7	0	0	1	1	2	2	1	2	2
Dades	UD	M	1	2	G	R	4	4	4	6	0	0	1	1	2	2	1	2	2
Dades	UD	M	1	4	RG	R	5	4	4	NA	0	1	1	1	2	2	2	3	2
Dades	UD	F	1	2	G	R	4	4	4	9	NA	0	1	2	3	3	3	3	3
Dades	UD	F	1	4	G	R	4	4	4	7	0	0	1	2	2	2	2	3	2
Dades	UD	M	0	2	G	R	4	5	4	9	0	0	1	2	3	3	2	3	3
Dades	UD	M	1	3	GTr	R	5	5	4	8	0	0	0	2	2	2	2	3	3
Dades	UD	M	0	2	GTr	R	5	5	4	7	0	0	0	2	2	2	2	3	3
Dades	UD	M	NA	2	G	R	3	4	4	6	0	0	1	1	2	2	2	3	2
Mgoun	UD	F	0	2	G	R	4	4	4	6	0	0	0	1	2	2	2	2	3
Mgoun	UD	M	0	3	G	R	4	NA	4	7	0	0	0	0	2	2	2	2	2
Mgoun	UD	M	1	3	G	R	4	4	4	6	0	0	0	0	2	2	2	2	1

Table S 4.4. (continued)

Site	SB	G	O	A	SDr	SIr	WDr	WIr	Crop	Health	Salty	Physical	Emotional	SatHealth	SatQuantity	SatQuality	SatAgriculture	SatEnvironment	SatLife
Mgoun	UD	F	NA	2	G	R	4	4	4	6	0	0	0	0	2	2	2	2	2
Mgoun	UD	M	0	2	G	R	4	4	4	7	0	0	1	0	2	2	2	2	1
Mgoun	UD	F	0	2	G	R	3	4	4	6	0	0	1	0	2	2	2	2	2
Mgoun	UD	F	0	2	G	R	4	4	4	8	0	0	0	0	2	2	2	2	2
Mgoun	UD	M	1	3	G	R	3	4	4	5	0	0	1	0	2	2	2	2	2
Mgoun	UD	F	0	2	G	R	3	4	4	8	0	0	1	0	2	2	2	2	2
Mgoun	UD	M	1	2	G	R	3	4	4	6	0	0	1	0	2	2	2	2	2
Mgoun	UD	M	1	3	G	R	3	4	4	7	0	0	0	0	2	2	2	2	2
Mgoun	UD	M	0	2	G	R	3	4	4	8	0	0	0	0	2	2	2	2	2
Mgoun	UD	F	0	1	G	R	3	4	4	6	0	0	1	0	2	2	2	2	1
Skoura	UD	F	0	3	G	RG	4	4	4	6	0	0	0	0	2	2	2	2	2
Skoura	UD	F	NA	3	G	RG	4	4	4	7	0	0	1	0	2	2	2	2	2
Skoura	UD	F	0	2	G	RG	4	4	4	8	0	0	0	0	2	2	2	2	2
Skoura	UD	F	0	3	G	RG	4	4	4	6	0	0	0	0	2	2	2	2	2
Skoura	UD	F	0	2	G	RG	4	4	4	7	0	0	0	0	2	2	2	2	2
Skoura	UD	F	0	3	G	RG	4	4	4	7	0	0	0	0	2	2	2	2	2
Skoura	UD	F	0	3	G	RG	4	4	4	6	0	0	0	0	2	2	2	2	2
Skoura	UD	F	0	2	G	RG	4	4	4	8	0	0	0	0	2	2	2	2	2
Skoura	UD	F	NA	3	G	RG	4	4	4	8	0	0	0	0	2	2	2	2	2
Skoura	UD	F	0	3	G	RG	4	4	4	7	0	0	0	0	2	2	2	2	2
Skoura	UD	F	0	3	G	RG	4	4	4	8	0	0	0	0	2	2	2	2	2
Skoura	UD	F	0	2	G	RG	4	4	4	8	0	0	0	0	2	2	2	2	2
Tamnougalt	MD	M	1	2	G	RG	3	4	3	6	2	0	2	1	1	1	1	1	1
Tamnougalt	MD	F	1	3	G	RG	3	4	3	8	1	NA	0	1	1	1	1	1	1
Tamnougalt	MD	M	1	3	G	RG	3	4	3	6	2	0	2	0	1	1	1	1	1
Tamnougalt	MD	M	1	2	G	RG	3	4	3	8	2	0	2	0	1	1	1	1	1
Tamnougalt	MD	M	1	2	G	RG	3	4	3	8	2	0	2	0	1	1	1	1	1
Tamnougalt	MD	M	1	3	G	RG	3	4	3	6	2	0	2	0	1	1	1	1	1
Tamnougalt	MD	M	1	3	G	RG	3	4	3	5	2	0	2	0	1	1	1	1	1
Tinzouline	MD	M	1	3	G	G	3	3.5	3	5	1	1	2	0	0	0	0	2	1
Tinzouline	MD	M	0	4	G	R	6	1	5	10	0	0	0	0	0	0	0	0	0
Tinzouline	MD	F	1	2	G	G	4	3	3	8	1	1	2	0	1	0	1	2	1
Tinzouline	MD	F	1	3	G	G	4	3	3	8	1	1	2	0	1	0	1	2	1
Tinzouline	MD	F	1	4	G	G	4	3	3	8	1	1	2	0	1	0	1	2	1
Tinzouline	MD	F	1	3	G	RG	6	6	2	10	1	0	2	2	0	1	0	0	1
Tinzouline	MD	M	1	2	G	G	3	1	2	9	1	0	2	0	0	0	0	2	2
Tinzouline	MD	M	1	3	G	RG	3	2	3	10	1	0	2	0	0	0	0	0	2
Tinzouline	MD	M	0	1	G	G	3	2	2	10	1	0	2	2	1	1	0	0	2
Tinzouline	MD	M	1	3	G	RG	4	3	4	9	0	0	0	2	1	2	2	1	2
Tinzouline	MD	M	1	3	G	G	4	4	4	NA	0	0	2	2	0	1	1	0	2
Ternata	MD	M	1	3	G	G	3	4	2	7	2	0	2	2	0	0	0	1	1
Ternata	MD	M	1	3	G	G	3	4	2	7	2	0	2	2	0	0	0	1	1

Table S 4.4. (continued)

Site	SB	G	O	A	SDr	SIr	WDr	WIr	Crop	Health	Salty	Physical	Emotional	SatHealth	SatQuantity	SatQuality	SatAgriculture	SatEnvironment	SatLife
Ternata	MD	M	1	3	G	G	3	4	2	7	2	0	2	2	0	0	0	1	1
Ternata	MD	M	1	3	G	G	3	4	2	7	2	0	2	2	0	0	0	1	1
Ternata	MD	F	0	2	G	G	2	2	4	6	2	1	2	2	0	0	0	1	0
Ternata	MD	F	0	2	G	G	4	4	4	NA	0	0	2	2	1	1	1	1	1
Ternata	MD	M	1	3	G	G	4	4	4	5	0	0	2	1	0	0	0	0	2
Ternata	MD	M	1	4	G	G	4	4	4	5	0	0	2	1	0	0	0	0	2
Ternata	MD	M	1	4	G	G	4	4	4	6	0	0	2	1	0	0	0	0	2
Ternata	MD	M	1	4	G	G	4	4	4	6	0	0	2	1	0	0	0	0	2
Ternata	MD	M	0	4	G	G	4	4	4	7	0	0	2	1	0	0	0	0	2
Ternata	MD	M	0	4	G	G	4	4	4	7	0	0	2	1	0	0	0	0	2
Ternata	MD	F	1	4	G	G	3	4	4	NA	0	0	2	0	0	2	0	NA	NA
Ternata	MD	M	0	2	G	G	4	4	4	8	0	0	2	1	1	0	0	2	2
Ternata	MD	F	1	3	G	G	4	5	3	7	0	0	2	0	0	2	0	0	2
Fezouata	MD	F	0	2	G	RG	3	3	3	6	0	0	1	2	1	1	1	2	2
Fezouata	MD	M	0	3	Ta	G	5	3	3	9	0	0	0	3	3	3	2	NA	0
Fezouata	MD	M	0	2	G	G	2	2	1	10	2	0	2	1	0	1	1	1	1
Fezouata	MD	M	0	2	G	G	2	1	2	7	0	2	2	NA	NA	NA	NA	NA	1
Fezouata	MD	M	0	3	G	G	3	3	3	5	2	1	1	2	1	0	1	1	1
Fezouata	MD	M	0	4	G	RG	3	3	2	5	2	1	1	1	1	1	1	1	1
Fezouata	MD	M	1	4	G	RG	4	2	2	5	2	0	1	2	1	1	1	1	2
Fezouata	MD	F	0	3	G	RG	3	1	NA	7	2	1	2	2	1	2	1	1	2
Fezouata	MD	F	1	3	G	RG	3	1	1	6	2	1	2	1	0	2	0	2	2
Fezouata	MD	M	0	2	G	RG	4	2	3	8	2	1	2	1	0	0	0	1	0
Fezouata	MD	M	0	1	G	RG	4	2	3	8	2	1	2	1	0	0	0	1	1
Fezouata	MD	F	0	2	G	G	4	2	2	6	2	0	2	0	0	0	1	1	2
Fezouata	MD	M	0	3	G	G	3	1	1	10	2	1	2	0	0	1	0	0	0
Fezouata	MD	M	1	4	G	G	3	2	2	6	2	2	2	0	0	0	0	0	0
Fezouata	MD	F	0	4	G	G	4	2	1	7	1	0	0	0	0	0	0	0	1
Fezouata	MD	M	0	2	Ta	G	6	3	3	10	1	0	2	0	1	2	1	0	1
Fezouata	MD	M	1	4	Ta	G	6	1	3	5	0	0	2	0	2	2	1	0	2
Fezouata	MD	M	0	2	Ta	G	6	3	3	10	0	0	2	0	2	2	2	0	1
Fezouata	MD	F	1	4	Ta	G	6	1	3	6	0	0	2	1	1	1	1	0	1
Fezouata	MD	M	0	2	Ta	G	4	3.5	4	9	0	0	2	1	1	2	1	1	0
Fezouata	MD	M	1	4	Ta	G	4	3	4	8	0	0	0	1	2	1	2	2	2
Fezouata	MD	M	1	3	Ta	G	4	3	3	9	0	0	1	1	0	1	1	2	2
Fezouata	MD	M	1	4	GTa	G	4	2	3	10	0	0	1	0	0	0	0	0	2
Akka	LD	M	0	3	Ta	RG	4	4	3	9	0	1	1	0	3	3	2	2	2
Akka	LD	M	0	3	Ta	RG	4	4	3	9	0	1	1	0	3	3	2	2	2
Akka	LD	M	0	3	Ta	RG	5	5	4	9	0	0	0	0	3	3	3	3	2
Akka	LD	M	0	2	Ta	RG	4	4	4	NA	0	0	0	1	2	2	2	2	2
Akka	LD	M	0	2	Ta	RG	5	3	3	6	0	1	0	0	2	3	2	2	1
Akka	LD	M	0	2	Ta	RG	4	5	NA	9	0	1	0	0	3	3	2	3	3
Akka	LD	M	0	2	Ta	RG	4	4	3	8	0	0	0	0	3	3	2	2	3

Table S 4.4. (continued)

Site	SB	G	O	A	SDr	SIr	WDr	WIr	Crop	Health	Salty	Physical	Emotional	SatHealth	SatQuantity	SatQuality	SatAgriculture	SatEnvironment	SatLife
Akka	LD	M	0	3	Ta	RG	4	3.5	3	7	0	0	0	1	3	3	2	3	2
Akka	LD	M	0	2	Ta	RG	5	4	3	8	0	0	0	1	2	2	2	2	2
Akka	LD	M	1	3	Ta	RG	6	5	5	6	0	0	0	0	3	3	3	3	3
Akka	LD	M	0	4	Ta	RG	6	6	5	5	0	0	0	0	3	3	3	3	2
Akka	LD	M	0	3	Ta	R	5	3	4	8	0	0	1	0	3	3	3	2	2
Mrimima	LD	M	0	4	G	O	2	3	4	6	2	0	1	0	2	1	0	0	2
Mrimima	LD	M	0	2	G	G	2	6	4	9	1	0	2	0	3	0	3	1	2
Mrimima	LD	M	0	1	G	G	1	3	3	10	1	2	2	0	3	1	3	0	2
Mrimima	LD	M	0	2	G	G	3	3	4	7	1	0	1	0	3	1	3	1	2
Mrimima	LD	M	0	2	G	G	3	3	2	9	1	1	1	0	3	0	0	0	1
Mrimima	LD	M	0	2	G	G	3	2	3	NA	2	2	0	0	0	1	0	0	0
Mrimima	LD	F	0	2	G	G	3	2	3	NA	2	2	0	0	0	1	0	0	0
Mrimima	LD	F	0	2	G	G	3	2	3	NA	2	2	0	0	0	1	0	0	0
Mrimima	LD	F	0	2	G	G	3	2	3	NA	2	2	0	0	0	1	0	0	0
Mrimima	LD	F	0	2	G	G	3	2	3	NA	2	2	0	0	0	1	0	0	0
Mrimima	LD	F	0	2	G	G	3	2	3	NA	2	2	0	0	0	1	0	0	0
Mrimima	LD	F	0	2	G	G	6	6	4	7	1	1	2	0	0	3	2	3	1

Table S 4. 5. Pearson/Spearman correlation table showing correlation coefficients with significance values (*** p<0.001, ** p<0.01, * p<0.05, ° p<0.1). WQI = Water Quality Index, BQI = Biological Quality Index, HSI = Human Satisfaction Index, Sat categories are for satisfaction with health care, quality and quantity of water resources, agricultural production possibilities, conditions of the natural environment and life overall for all 17 sites (mean values per site).

Pearson	WQI	BQI	HSI	SatHealth	SaQuality	SatQuantity	SatAgriculture	SatEnvironment	SatLife
WQI	1	0.6*	0.25	0.3	0.13	0.14	0	0.41	0.4
BQI		1	0.5	0.24	0.38	0.36	0.53°	0.6°	0.66°
HSI			1	0.43	0.94***	0.92***	0.88***	0.95***	0.87***
SatHealth				1	0.13	0.12	0.04	0.46	0.48
SaQuality					1	0.99***	0.91***	0.84**	0.76**
SatQuantity						1	0.88***	0.8**	0.73*
SatAgriculture							1	0.79**	0.68*
SatEnvironment								1	0.93***
SatLife									1
Spearman	WQI	BQI	HSI	SatHealth	SaQuality	SatQuantity	SatAgriculture	SatEnvironment	SatLife
WQI	1	0.56*	0.27	0.36	0.27	0.24	0.13	0.18	0.29
BQI		1	0.21	0.1	0.35	0.34	0.4	0.32	0.48
HSI			1	0.47	0.92***	0.91***	0.71*	0.87***	0.59*
SatHealth				1	0.21	0.18	-0.09	0.35	0.32
SaQuality					1	1***	0.77**	0.94***	0.71*
SatQuantity						1	0.76**	0.93***	0.71*
SatAgriculture							1	0.67*	0.39
SatEnvironment								1	0.85***
SatLife									1

Appendix 5. 1. First and second-tier variables of a social-ecological system. (Source: McGinnis and Ostrom, 2014).

First-tier variable	Second-tier variables
Social, economic, and political settings (S)	S1–Economic development S2 – Demographic S3 – Political S4 – Other governance S5 – Markets S6 – Media organizations S7 – Technology
Resource systems (RS)	RS1 – Sector (e.g., water, forests, pasture, fish) RS2 – Clarity of system boundaries RS3 – Size of resource system RS4 – Human-constructed facilities RS5 – Productivity of system RS6 – Equilibrium properties RS7 – Predictability of system dynamics RS8 – Storage characteristics RS9 – Location
Governance systems (GS)	GS1* – Policy area GS2*– Geographic scale of governance system GS3* – Population GS4* – Regime type GS5* – Rule-making organizations GS6*– Rules-in-use GS7* – Property-rights systems GS8*– Repertoire of norms and strategies GS9* – Network structure GS10* – Historical continuity
Resource units (RU)	RU2 – Growth or replacement rate RU3 – Interaction among resource units RU4 – Economic value RU5 – Number of units RU6 – Distinctive characteristics RU7–Spatial and temporal distribution
Actors (A)	A1– Number of relevant actors A2 – Socioeconomic attributes A3 – History or past experiences A4 – Location A5 – Leadership/entrepreneurship A6 – Norms(trust-reciprocity) /social capital A7– Knowledge of SES/mental models A8– Dependence on the resource A9 – Technologies used to access the resource
Action situations: Interactions (I) → Outcomes (O)	I1 - Harvesting I2 – Information sharing I3 – Deliberation processes I4 – Conflicts I5 – Investment activities I6 – Lobbying activities I7 – Self-organizing activities I8 – Networking activities I9 – Monitoring activities I10 – Evaluative activities O1 – Social performance measures (e.g., efficiency, equity, accountability, sustainability) O2 – Ecological performance measures (e.g., overharvested, resilience, biodiversity, sustainability) O3 – Externalities to other SESs

Appendix 5. 2. Incentive categories scheme (Adapted from Kerr et al., 2012; Rapoport et al., 2001 ; Travers et al., 2011; Vatn, 2009).

Incentives included	Definition of the incentive
FINANCIAL/ECONOMIC INCENTIVES	
Tax Breaks	Regulations may offer tax incentives to aquifer users who demonstrate responsible water use practices or invest in water-saving technologies. These tax breaks reduce the financial burden and encourage users to adopt more sustainable approaches.
Environmental permits	Users who comply with environmentally friendly practices and adhere to specific guidelines may receive permits that grant them greater access to groundwater resources or other benefits.
Subsidies	Financial support from governments or organizations can be provided to aquifer users for adopting technologies or practices that promote water conservation and sustainable resource management.
Rebates	Users who reduce their water consumption or implement water-saving measures may receive rebates on their water usage fees or related expenses.
Performance-Based Rewards	Aquifer users who achieve predefined conservation or sustainability targets may be rewarded with financial incentives or grants as a recognition of their efforts.
Legal Incentives	The legal incentives are provided through the regulatory frameworks, including penalties for non-compliance, property rights, and enforcement mechanisms.
NON-FINANCIAL INCENTIVES	
Social Incentives	The social incentives embedded in the regulatory frameworks, such as community recognition, reputation, or social pressure for adhering to rules. These may influence users' behavior and cooperation
Information Sharing	Stakeholders are encouraged to share data, knowledge, and experiences related to aquifer management. Transparent information exchange fosters trust, collaboration, and informed decision-making.
Joint Monitoring	Collaborative monitoring programs involve stakeholders in data collection and analysis. This shared responsibility enhances understanding and ownership of groundwater management processes.
Performance-Based Contracts	Agreements may include performance-based contracts where users commit to specific conservation or sustainability measures. Meeting these targets can lead to benefits such as extended water use permits or priority access to resources.
Technical Assistance	Access to technical expertise and support can be provided to aquifer users to help them adopt sustainable practices, implement water-saving technologies, and address challenges effectively.

Appendix 5.3. Actor Mapping for the MDV cases.

Case	Actors	Profile/Characteristics	Interests	
Faija case	Collective land-right-holders	**Category I** "Farmers" settled in Faija or Zagora city	Land-holders and members of tribes in Faija that express attachment to the land. They plan to work in Faija in the long-term and have high dependence on agriculture. They mainly grow watermelon but they tend to diversify crops (date palms, other trees, vegetables). Farmers differ in the irrigated area (<0.5ha; <2ha; <5ha; <10ha; >10ha), water volume abstracted per year (ranging from 205m3 to 230,000m3), access to capital and irrigation infrastructure, and education level.	. Secure groundwater supply to continue with farming activities in the long-term. . Government should simplify the process to get licenses for wells. . Prevent control of the government over water abstraction because that would reduce their autonomy to make decisions about which crops to farm and changes in size of cultivated area. . Some farmers have debts with agricultural input suppliers and merchants. These debts discourage farmers to reduce their watermelon cultivated area. . Replacement of watermelon is only possible if the government finances this transition. . Legitimize the use of groundwater for those who have a long-term interest in the area (those planting trees) and delegitimize those who are only doing seasonal watermelon using a lot of water. . Farmers want more dams to capture rain water and increase water supply in Faija.
		Category II "Businessmen"	These are landholders and members of the tribes in Faija. Some are settled in Zagora, some in other cities. They don't identify themselves as farmers but as businessmen. They invest in watermelon seasonally as a line of business. They have other sources of income & agriculture in Faija is not necessarily the main activity. They do not have an attachment with land in Faija and are not interested in working in agriculture in the long term.	. Make as much gains on watermelon business as possible during the agricultural campaign (Dec-Apr/May).
		Category III Land-holders renting the land	Some land-right holders do not have the capital to finance the watermelon production by themselves or are not interested in engaging in watermelon production directly. These land-holders work with non-tribe members (denominated "barrani" in Amazigh) who work as investors in watermelon production in Faija.	. Some land-holders start renting land or establishing co-management arrangements with investors as a way to form their own capital to continue working as farmers in the long-term. In this sense, they have a short-term interest in capital formation. Limits on area to cultivate watermelon can go against this interest. . Other landholders are not interested in engaging in farming activities. They have other sources of income and their economic dependence on Faija groundwater is minor. However, rules that limit the area cultivated with watermelon can also go against their interest to rent land, which is mainly rented by foreign investors.

Appendix 5.3. (Continued).

		Category IV Private land-right-holders	Most are residents of Zagora City. Some have professions (i.e. school teachers), or are businessmen in different sectors. These farms were bought from the Mssoufa tribe during the 1990s and are devoted to growing date palm as the main crop. However, these private owners have increased the irrigated area with watermelon in recent years.	Interviewees expressed their desire to continue practicing agriculture in the long term in Faija and caring for the sustainability of the aquifer
		Category V Non-land-holders working as investors in Watermelon	They either rent the land in Faija from landholders or engage in co-farming arrangements with them. Some work with several land-holders at the same time, which gives them access to big extensions of land. They do not have an attachment to the land and identify themselves more as businessmen than farmers. Most of them are not settled down in the area. Not interested in resource sustainability in the long-term. They show a "groundwater mining behavior".	Make as many gains on the watermelon business as possible during the agricultural campaign (Dec-Apr/May).
		Category VI Providers of agricultural inputs	Irrigation infrastructure, well-diggers, solar panels providers, fuel providers.	These actors benefit indirectly from watermelon production. They are interested in the continuity of this activity that is a source of income for them.
		Category VII Intermediary merchants	People buy the harvest of the farmer and transport it to the markets. Commonly, these merchants play the role of funders, paying in advance for the harvest.	These actors are interested in the continuity of watermelon farming in Faija.

Appendix 5.3. (Continued).

		Category IX Governmental organizations	The National Office of Water and Electricity (ONEE in French) operates in Faija several wells for drinking water production. Ministry of Interior (MININTER) through Chikh and Mokadem in tribes. They represent the Caid in the area. Their role is to ensure security and order in the local area by monitoring and enforcing statutory rules.	Secure the production of drinking water. Chikh and Moqadems are representatives of the government but also members of the tribe, also working on watermelon farming. Their interests combine their role of preventing and solving conflicts in Faija and their personal interests as farmers and tribe members.
M'hamid case	Farmers		Farmers in M'hamid are practicing agriculture for subsistence mostly for the last 7 to 10 years. Most of them are practicing other activities besides farming since farming can't be guaranteed to bring income to the household all the time. They have low dependency on farming and water.	. Secure some groundwater supply to continue with subsistence farming activities as long as possible. . Secure a source of food while making their main income from other activities such as construction. Secure their identity as farmers of the oasis.
	Touristic facilities owners		Owners of touristic facilities such as hotels, campings,	. Secure water supply for their touristic facilities and guarantee offering proper and full services for visitors, to secure their income.
Fezouata case	Farmers	Household farming	Local inhabitants practiced subsistence farming and selling a small part of it in the local markets. This is practiced besides other activities either inside the area such as teaching or construction, or outside the area in big cities. The farming activities are usually financed by remittances from family members working abroad and income made from other activities.	. Secure water and income to continue practicing farming and guarantee their well-being in the area. . Secure a source of income that will help finance their farming activities and other expenses. Secure their identity as farmers of the oasis.
		Business farming	Local inhabitants practice farming as a primary source of income. They are owners of farms and produce dates and other products that are sold on local and national markets.	. Secure groundwater supply to continue practicing farming and making profits from dates mainly. . Secure their identity as farmers of the oasis.

Appendix 5. 4. Quotes from interviews supporting the characterization of the SESs.

SES variable	Quotes
Resource System and Resource Units of M'hamid	**N° 1**: *"If we want everything to get back to normal, we need rain up there, in the mountains. I'm talking from Ouarzazate, the dam of Al Mansour Eddahbi until down here, because if rain water reached the dam of Al Mansour Eddahbi, it would eventually reach the Oued [river] here. If there's a great amount of rain water, it would pass from the dam through the Oued, and then the water would get to the phreatic zone, which would be absorbed by the roots of the palm trees"* (Manager collective well, Talha, 2022).
	N°2*: "There's a canal, and the releases from the dam, about three times per year. But lately, the dam has become empty so we got just one or two releases in these last two years, and the well. There are some people who built their own wells, but for me, I didn't build my own well. I get water from this* [collective] *well with solar panels* (Manager collective well, Talha, 2022).
The governance system of M'hamid	**N°3:** *"The first collective well was made in Talha village that has been for 7 years now. In Ouled Mahiya village, two more collective wells were constructed this year, and are not operating yet. One in Mhamid village, another in Zaouia Al hana village, and another one in Lahnanich village. One is in the process in Ragabi village. You can see it once you enter Mhamid. They all follow the same community rules." (Collective well manager, Talha, 2022)*
Outcomes of M'hamid	**N°4:** *Yeah, the problem is the quantity of water, the water went down, we rely on the Palm trees … but the roots of the palm trees can't reach the water anymore, this year you can't find water underground until you reach 12m, and last year it was 11m, so for only one year the water went down by 1m"* (Manager collective well Talha, 2022).

Appendix 5. 5. SES complementary variables.

Case study	Institution	SES key characteristics				Outcomes	
		Water infrastructure	Sector	System boundaries/size	Harvesting levels	Interactions	State of the aquifer
Faija	Aquifer contract	Private wells	Commercial agriculture Drinking water production	Clear system boundaries Clear user community	Farmers are still finding enough water of good quality for their productive activities.	Information sharing: informal, empirical, not systematic. Monitoring: no water meters installed. Monitoring of illegal wells is loosely implemented and is circumvented by users. Deliberative processes: no formal mechanisms for co-decision-making between state & users. Decisions made by the government. Conflict: between tribes over control of land. Experience between local farmers and government over public drinking-water wells.	Deficit of 5Mm3/year due to over-abstraction and quality deterioration due to agricultural pollution.

Appendix 5.5. (Continued).

Case study	Institution	Water Infrastructure	Sector	System Boundaries/size	Harvesting Levels	Interactions	State of the aquifer
Fezouata	Statutory laws	Private wells Eddahbi Dam and canal system affects recharge rate of aquifer	Commercial (dates) and subsistence agriculture	Diffuse system boundaries. Diffuse user community	Water tables are dropping and salinity concentration increases but farmers are still able to find water in wells.	Information sharing: no formal institutions in place. Empirical information is collected by water users and shared with friends in informal conversations. Monitoring: no water meters installed. Monitoring of illegal wells in charge of government authorities but it is loosely implemented and is circumvented. Deliberative processes: Decisions on groundwater abstraction are taken individually. No collective action in place.	Interviewees report: that sectors of the aquifer show signs of depletion and palm trees are dying.
M'hamid	Self-governance organization. Limited intervention of the state.	Collective wells Eddahbi Dam and canal system affect the recharge rate of the aquifer.	Subsistance agriculture	Diffuse system boundaries . Clear user communities	Farmers find it very difficult to find groundwater.	Information sharing: no information sharing between users and government. No sharing between users of different collective wells. Monitoring: users monitor water availability in wells and unauthorized abstractions. Sanctions based on customary rules. Deliberative processes: decisions made by collective wells boards, whose members are elected by voting.	The groundwater inflows and outflows at a balance point (ABHSMD,2010) of 225.4l/s Salinity concentration reaches a max. of 12.16g/l, with an average of 5g/l (ABHSMD, 2010).

Author Contributions

Article 1:

Mahjoubi, I.; Bossenbroek, L.; Berger, E.; Frör, O. Analyzing Stakeholder Perceptions of Water Ecosystem Services to Enhance Resilience in the Middle Drâa Valley, Southern Morocco. Sustainability 2022, 14, 4765. https://doi.org/10.3390/su14084765.

Contributions: Mahjoubi, I., Bossenbroek, L., Berger, E., and Frör, O., Conceptualisation; **Mahjoubi, I.,** methodology, software, formal analysis, investigation, data curation, visualization, writing—original draft preparation; **Mahjoubi, I., Bossenbroek, L., Berger, E., and Frör, O.,** resources; **Bossenbroek, L., Berger, E., and Frör, O.,** Supervision, review and editing, project administration; **Berger, E,** Funding acquisition; All authors have read and agreed to the published version ofthe manuscript.

Article 2:

Mahjoubi, I., Frör, O. Ecosystem service change from lost surface water for farming in the Middle Drâa valley, southern Morocco: An economic valuation through a Replacement Cost Approach (revisions submitted 29/05/2024).

Contributions: Mahjoubi, I., and Frör, O., Conceptualisation, methodology, resources; **Mahjoubi, I.,** Software, formal analysis, investigation, data curation, visualization, writing-original draft preparation; **Frör, O.,** Supervision, validation, project administration, funding acquisition; **Mahjoubi, I., and Frör, O.,** writing—review and editing; All authors have read and agreed to the published version ofthe manuscript.

Article 3:

Kaczmarek, N., I. Mahjoubi, M. Benlasri, M. Nothof, R. B. Schäfer, O. Frör, & E. Berger, 2023. Water quality, biological quality, and human well-being: Water salinity and scarcity in the Draa River basin, Morocco. Ecological Indicators Elsevier 148: 110050. https://doi.org/10.1016/j.ecolind.2023.110050.

Contributions: Kaczmarek, N., Conceptualisation, methodology, validation, formal analysis, investigation, writing - original Draft, writing - review & editing, visualization; **Mahjoubi, I.,** Conceptualization, methodology, validation, investigation, writing - original draft, writing - review & editing; **Benlasri, M.,** Investigation; **Nothof, M.,** Methodology, validation, formal analysis, investigation; **Schäfer, B. R.,** Methodology, validation, formal analysis, writing - review & editing, supervision, funding acquisition; **Frör, O.,** Methodology, validation, writing - review & editing, supervision, funding acquisition; **Berger, E.,** Conceptualization, methodology, validation, writing - original draft, writing - review & editing, supervision, project administration, funding acquisition;

Article 4:

Silva-Novoa Sanchez, L. M.; Mahjoubi, I.; Frör, O.; Bossenbroek, L.; Schilling, J. P.; Berger, E.; What groundwater governance challenges and opportunities arise in arid regions? Lessons from the Middle Drâa Valley, Morocco.

Contributions: Silva-Novoa Sánchez, L.M. and Mahjoubi, I. Equal contribution in conceptualisation, methodology, validation, formal analysis, investigation, writing - original Draft, writing - review & editing, visualization. **Silva-Novoa Sánchez, L.M**. Conceptualization and analysis of components of the Social-Ecological-System (SES) Framework and investigation in Faija and Fezouata. **Mahjoubi, I**. Analysis of the governance system using the incentive adequacy approach and investigation in Fezouata and M'hamid. **Frör, O.** Conceptualization, methodology and review of formal analysis. **Bossenbroek, L., Schilling, J., and Berger, E.** Review, editing, and validation of the manuscript. All authors approved the final version of the manuscript.

Curriculum Vitae

Imane Mahjoubi

Education

11/24 – Present	**Post-Doctoral research** Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau - Institute for Environmental Sciences, Germany Cultural Ecosystem Services in the Middle Draa Valley. In the framework of the SALIDRAA 2 project.
2019 – 2024	**Ph.D in Environmental Economics** Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau - Institute for Environmental Sciences, Germany (November 2019 – October 2024) PhD Thesis project: “Water Ecosystem Services under the Effect of water scarcity in the Drâa Watershed in Morocco”. In the framework of the SALIDRAA 2 research project. • Sustainability, socio-economic analysis, social-ecological systems, quantitative and qualitative data collection and analysis, inter and transdisciplinarity.
2017 – 2019	**Master's degree in Environmental Economics** University Caddi Ayyad, Marrakech, Morocco; Faculty of Economics and Social and Legal Sciences. Master thesis project: “Economic valuation of ecosystem services applied for Zerhoun Forest, Meknes, Morocco”.
2015 – 2016	**Bachelor's degree in International Finance** High School of Technology (EST) Meknes, Morocco Bachelor’s Thesis project: “Waste public tax collection”.
2013 – 2015	**University degree in Economics** High School of Technology (EST), Meknes, Morocco.

Professional Experience

December 2023 — **External review of IPBES nexus assessment drafts: Assessment of the interlinkages among biodiversity, water, food, and health.**
In preparation for an online stakeholder dialogue (December 18th,2023).
Freshwater Biodiversity Observation Network (FWBON).

January 2019 — **Assistant and participant in USAID career center**
Soft skills - Personal and professional development training.
Faculty of Economics, Marrakech, Morocco.

March 2019 — **Training in "Economic valuation of forest's ecosystem services"**
Provincial Directorate for Waters and Forests and the fight against desertification. Meknes, Morocco.

Scientific Publications

- **Mahjoubi, I**.; Bossenbroek, L.; Berger, E.; Frör, O. Analyzing Stakeholder Perceptions of Water Ecosystem Services to Enhance Resilience in the Middle Drâa Valley, Southern Morocco. Sustainability 2022, 14, 4765. https://doi.org/ 10.3390/su14084765.
- Kaczmarek, N., **I. Mahjoubi**, M. Benlasri, M. Nothof, R. B. Schäfer, O. Frör, & E. Berger, 2023. Water quality, biological quality, and human well-being: Water salinity and scarcity in the Draa River basin, Morocco. Ecological Indicators Elsevier 148: 110050. https://doi.org/10.1016/j.ecolind.2023.110050.

International Scientific Conferences

- **Euro-Mediterranean Conference for Environmental Integration (EMCEI) 2024 Marrakech:** Mahjoubi, I., Frör, O. Ecosystem service change from lost surface water for farming in the Middle Drâa valley, southern Morocco: An economic valuation through a Replacement Cost Approach. May 15-18, 2024, Marrakech, Morocco.
- **2nd meeting of the Iberian Ecological Society (SIBECOL) and the Iberian Association of Limnology (AIL) 2022:** Berger, E., Bossenbroek, L., Moumane, A., Silva-Novoa, LM., and Mahjoubi, I. "Combining remote sensing and ethnography to study social-ecological flows in the Draa River Basin, Morocco." July 3-8, 2022, Aveiro, Portugal.
- **Aquatic Science Meeting ASLO 2021:** Mahjoubi, I., Frör, Ö., Berger, E., and Bossenbroek, L. "Enhancing the resilience of water ecosystem services: An analysis of stakeholders' perceptions in the Middle Draa Valley, Southern Morocco." July 22-27, 2021, virtual conference.